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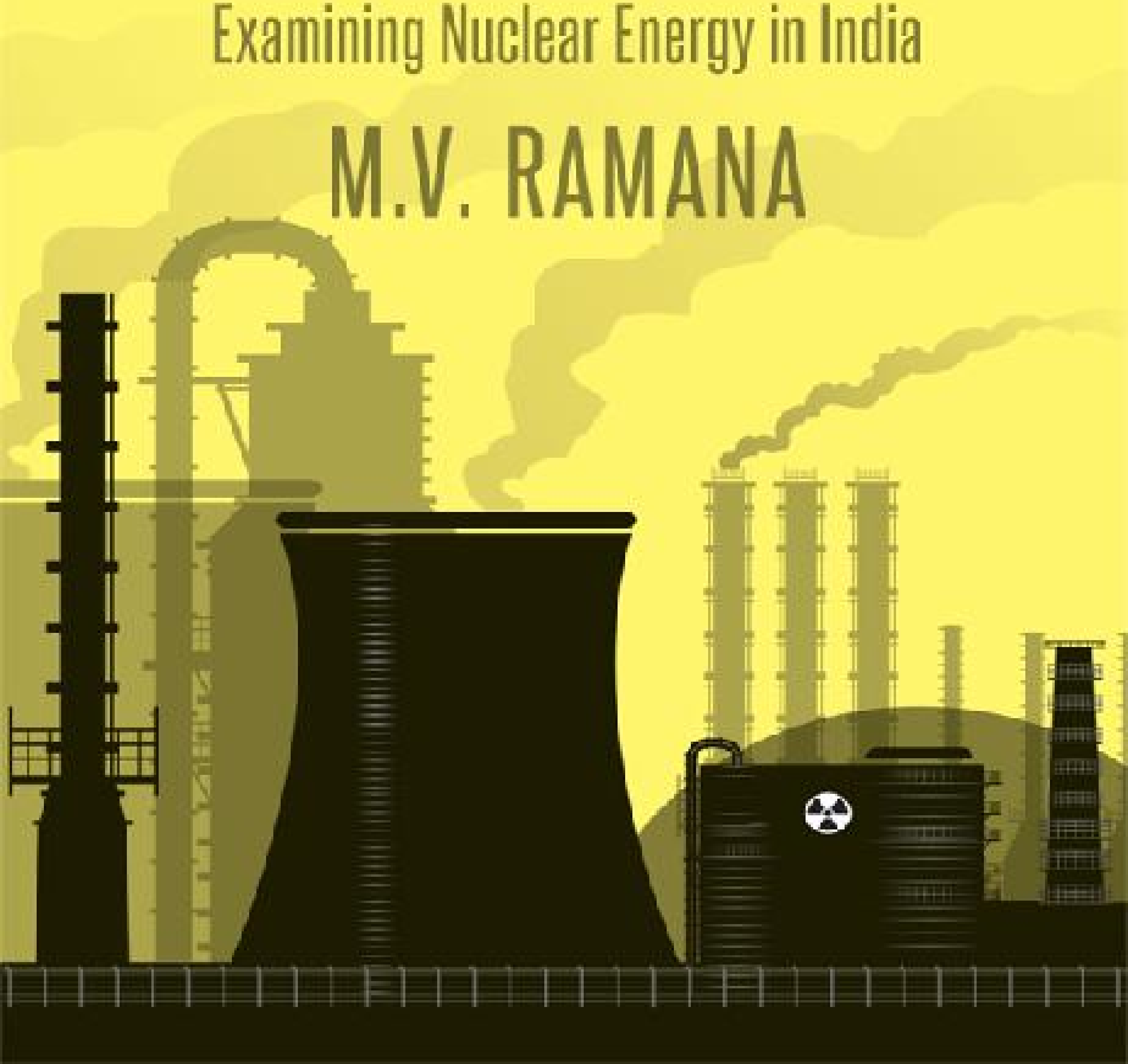
'Authoritative, state of the art analysis' **JONATHAN SCHELL**

THE POWER OF PROMISE

Examining Nuclear Energy in India

M.V. RAMANA



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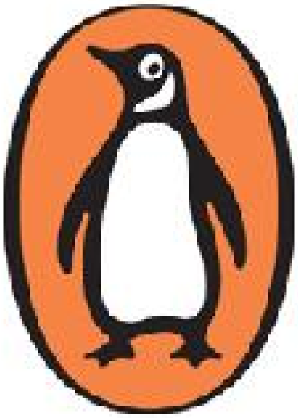

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M.V. RAMANA

The Power of Promise
Examining Nuclear Energy in India

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Advance Praise for the Book

‘Solidly researched and meticulously argued, *The Power of Promise* is a landmark in the debate on nuclear energy in India. Ramana has managed to make complex technological, economic and other issues intelligible with great lucidity. Essential reading for everyone concerned about the difficult energy choices we confront today.’

—Amita Baviskar, sociologist of environment and development, Institute of Economic Growth

‘*The Power of Promise* will serve as the authoritative source for many years to come on India’s civilian nuclear power program. Ramana’s comprehensive and expert history of India’s efforts to establish nuclear power as the modern energy source to drive development is without peer. With style and detail he tells the story of false starts, overblown claims, accidents, cost overruns, and, despite the difficulties, continued hope that nuclear power will be the answer to India’s economic underdevelopment. This is a must-read for all who are interested in the future of nuclear power in India—and around the world.’

—Kennette Benedict, executive director and publisher of the *Bulletin of the Atomic Scientists*

‘*The Power of Promise* is as timely as it is important. I have no doubt that it will come to be regarded as a landmark, not only in the debates on nuclear and energy issues, but also in the history and sociology of Indian science.’

—Amitav Ghosh (www.amitavghosh.com/blog)

‘M.V. Ramana has provided a concise history of the Indian nuclear power program, along with insights and analyses only very few can logically put together. Very readable and a bold depiction of events and facts.’

—A. Gopalakrishnan, former chairman, Atomic Energy Regulatory Board

‘Combining sober prose with solid research and sharp analysis, *The Power of Promise* is an authoritative and comprehensive study of India’s nuclear energy industry. This is a story of, among other things, accidents, breakdowns, operational delays, cost overruns, and of large promises consistently broken or unfulfilled. This much celebrated industry is, on closer scrutiny, revealed to be the whitest of white elephants. There may still be political compulsions for having nuclear weapons as a “deterrent”; but, as M.V. Ramana’s outstanding work of scholarship so convincingly demonstrates, on environmental, ethical, and especially economic grounds, there is really no case for promoting nuclear energy in India.’

—Ramachandra Guha, author of *India After Gandhi*

‘The good news in this understated but devastating study is that the Indian nuclear establishment and its international backers cannot deliver the massive capability they have promised. The bad news is that their reckless speed in the face of rising local resistance can create disasters that could dwarf Fukushima.’

—Anand Patwardhan, documentary film-maker

‘*The Power of Promise* is an excellent work on the ongoing energy challenges being faced by the fast growing economy of India, and examines in detail the current policy of relying on nuclear energy as the saviour of its projected development program.’

—Admiral Ramdas, former Chief of Naval Staff

‘M.V. Ramana has captured in a readable, yet rigorous, manner, the saga of a nation’s obsession with nuclear energy. From the heady days of Jawaharlal Nehru and Homi Bhabha, to the current reality of an entrenched nuclear bureaucracy with virtually endless political power and patronage, and the serious challenges from growing resistance movements, *The Power of Promise* is a fascinating, well researched journey. A must read for all those who seriously seek a better understanding of our future energy options and factors at work under the surface.’

—Lalita Ramdas, former board chair, Greenpeace International; founding member, Greenpeace India

‘*The Power of Promise* is the first independent assessment of six decades of India’s nuclear programme. Based entirely on official and other published documents, this exhaustive work critically examines what the nuclear establishment has been promising all these years, what it has actually delivered, and its new promises over the next half century.’

—C. Rammanohar Reddy, editor, *Economic and Political Weekly*

‘Official disclosures on nuclear technology in India have tended to underplay the risks and the costs, and overplay the benefits. This has impaired the quality of political debate. Through his incisive analysis of what the nuclear establishment had promised in the past and what it could really achieve, M.V. Ramana has succeeded in creating an environment in which the discourse on the technology will get deepened and more sensible outcomes will emerge.’

—E.A.S. Sarma, former Secretary, ministry of power, Government of India

‘In *The Power of Promise*, the dream of a nuclear power “renaissance” in India runs into a thick wall of technical, economic and historical facts, and falls to the ground. The implications of this meticulously researched, thoughtfully argued, authoritative, state of the art analysis extend beyond India and even nuclear power itself to shed new light on the character and future of nuclear danger in its entirety.’

—Jonathan Schell, author of *The Seventh Decade: The New Shape of Nuclear Danger*

‘*The Power of Promise* is an unprecedented systemic analysis of underlying historical, technical, economic and political aspects of nuclear energy in India, and will be a pure work of reference. Don’t claim to know anything about India’s nuclear programme if you have not read this book yet.’

—Mycle Schneider, energy analyst and author of *World Nuclear Industry Status Report* series

‘This magisterial study, demonstrating a mastery of the existing literature and a sure grasp of the science and technologies involved, is now the single most authoritative account anywhere of the Department of Atomic Energy’s performance record and its claims to providing cheap, safe and plentiful electricity in the future.’

—Achin Vanaik, retired professor of International Relations and Global Politics, University of Delhi

List of Acronyms

AEC	Atomic Energy Commission
AECL	Atomic Energy Canada Limited
AERB	Atomic Energy Regulatory Board
AFR	Away from Reactor
AHWR	Advanced Heavy Water Reactor
AMD	Atomic Minerals Directorate
BARC	Bhabha Atomic Research Centre
BARCCIS	Bhabha Atomic Research Centre Channel Inspection System
BAU	Business as Usual
BEIR	Biological Effects of Ionizing Radiation
BFEA	BARC Facilities Employees Association
BHAVINI	Bharatiya Nabhikiya Vidyut Nigam
BHEL	Bharat Heavy Electricals Limited
BJP	Bharatiya Janata Party
BWR	Boiling Water Reactor
CAG	Comptroller and Auditor General
CANDU	Canada Deuterium Uranium
CCEA	Cabinet Committee on Economic Affairs
CDA	Core Disruptive Accident
CEA	French Atomic Energy Commission
CEA	Central Electricity Authority
CERC	Central Electricity Regulatory Commission
CHTR	Compact High Temperature Reactor
CIR	Canada India Reactor (subsequently renamed CIRUS)
CISED	Centre for Interdisciplinary Studies in

	Environment and Development
CITU	Confederation of Indian Trade Unions
CPIO	Central Public Information Officer
CRPF	Central Reserve Police Force
CSIR	Council of Scientific and Industrial Research
CWMF	Central Waste Management Facility (Kalpakkam)
DAE	Department of Atomic Energy
DCF	Discounted Cash Flow
DEFENDUS	Development-Focused, End Use-Oriented, and Service-Directed
DGMS	Directorate General of Mines Safety
DNA	Deoxyribonucleic Acid
EAC	Expert Appraisal Committee
EAR	Estimated Additional Resources
EBR-1	Experimental Breeder Reactor-1
ECCS	Emergency Core Cooling System
EIA	Environmental Impact Assessment
EPR	European/Evolutionary Pressurized Reactor
ESC	Energy Survey Committee
FBR	Fast Breeder Reactor
FBTR	Fast Breeder Test Reactor
FPC	Fuel Policy Committee
FV	Future Value
FWL	Footwall Lodeg
gCO_2e/kWh	Gramme of Carbon Dioxide Equivalent per Kilowatt-Hour
GCR	Gas-Cooled, Graphite-Moderated Reactor
GE	General Electric Company
GW	Gigawatts
HEPA	High Efficiency Particulate Air (Filter)
HEU	Highly Enriched Uranium
HLW	High-Level Waste
HRO	High Reliability Organization
HW	Heavy Water

HWB	Heavy Water Board
HWL	Hanging Wall Lode
HWP	Heavy Water Plant
IAEA	International Atomic Energy Agency
IARC	International Agency for Research on Cancer
IAS	Indian Administrative Service
ICRP	International Commission on Radiological Protection
IDPD	Indian Doctors for Peace and Development
IEP	Integrated Energy Policy
IGCAR	Indira Gandhi Centre for Atomic Research
IISc	Indian Institute of Science
ILW	Intermediate-Level Waste
INFCE	International Nuclear Fuel Cycle Evaluation
INTUC	Indian National Trade Union Congress
IR	Inferred Resources
ITER	International Thermonuclear Experimental Reactor
JOAR	Jharkhandi Organization against Radiation
JSPCB	Jharkhand State Pollution Control Board
KAPS	Kakrapar Atomic Power Station
KARP	Kalpakkam Atomic Reprocessing Plant
kPa	Kilopascals
KSU	Khasi Students' Union
kWh	Kilowatt-Hour
LET	Linear Energy Transfer
LEU	Low Enriched Uranium
LF	Load Factor (used interchangeably with capacity factor)
LLW	Low-Level Waste
LWGR	Light-Water-Cooled, Graphite-Moderated Reactors
LWR	Light Water Reactor
MAPS	Madras Atomic Power Station

MECL	Mineral Exploration Corporation Ltd
MECO	Montreal Engineering Company
MFBR	Metallic Fuelled Fast Breeder Reactor
MJ	Megajoules (million joules)
MoEF	Ministry of Environment and Forests
MoP	Ministry of Power
MOX	Mixed Oxide (a mixture of plutonium and uranium oxides)
MoU	Memorandum of Understanding
MTCR	Missile Technology Control Regime
MW	Megawatts (million watts)
NAPM	National Alliance of People's Movements
NAPS	Narora Atomic Power Station
NAT	Normal Accident Theory
NEA	Nuclear Energy Agency
NEAA	National Environment Appellate Authority
NEE	Nuclear Explosives Engineering
NEERI	National Environmental Engineering Research Institute
NEI	*Nuclear Engineering International*
NIOSH	National Institute for Occupational Safety and Health
NNPA	Nuclear Non-Proliferation Act
NPCIL	Nuclear Power Corporation of India Limited
NPL	National Physical Laboratory
NPT	Treaty on the Non-Proliferation of Nuclear Weapons
NSG	Nuclear Suppliers Group
NRX	National Research Experimental
NTPC	National Thermal Power Corporation
O&M	Operations and Maintenance
OBT	Organically Bound Tritium
OCC	Overnight Construction Cost
OECD	Organisation for Economic Co-operation and Development

OFBR	Oxide-Fuelled Fast Breeder Reactor
OP	Out-of-Pile time
OSHA	Occupational Safety and Health Administration
PFBR	Prototype Fast Breeder Reactor
PHWR	Pressurized Heavy Water Reactor
PMANE	People's Movement against Nuclear Energy
PMO	Prime Minister's Office
PNE	Peaceful Nuclear Explosive/Experiment/Explosionppm Parts per Million
PREFRE	Power Reactor Fuel Reprocessing (Facility)
PRIS	Power Reactor Information System
PU	Plutonium
PUREX	Plutonium and Uranium Recovery by Extraction
PV	Present Value
PWR	Pressurized Water Reactor
RAPS	Rajasthan Atomic Power Station
RAPS I	Rajasthan Atomic Power Station
RAR	Reasonably Assured Resources
RMD	Raw Materials Division
RRC	Reactor Research Centre
RTI	Right to Information
RTPS VII	Raichur VII Thermal Power Station
S3F	Solid Storage Surveillance Facility
SKV	Sampoorna Kranti Vidyalaya
SRC	Safety Review Committee
TAPS	Tarapur Atomic Power Station
TBP	Tributyl Phosphate
TDC	Turamdih Displaced Committee
THORP	Thermal Oxide Reprocessing Plant
TIFR	Tata Institute of Fundamental Research
TLD	Thermoluminescent Dosimeter
UCIL	Uranium Corporation of India Limited
UKAEA	United Kingdom Atomic Energy Authority

UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
UPA	United Progressive Alliance
USAEC	United States Atomic Energy Commission
USAID	US Agency for International Development
WANO	World Association of Nuclear Operators
WGEP	Working Group on Energy Policy
WTF	Waste Tank Farm

Introduction

In September 2009, while speaking at the inauguration of the International Conference on the Peaceful Uses of Atomic Energy in New Delhi, Prime Minister Manmohan Singh stated that India could have 470 gigawatts (GW) of nuclear power capacity by 2050. To put this in perspective, the current nuclear capacity in the country—more than sixty years after the atomic energy programme was established—is just 4.78 GW, a small fraction of the total electricity generation capacity of 205 GW.[1] The projected capacity in 2050 would represent an increase by a factor of hundred, and would also exceed the global nuclear power capacity today. Is this feasible or even desirable? More generally, is nuclear power likely to become a significant source of electricity for the country?

These questions have become very important over the last few years in the wake of what has popularly been dubbed the 'US–India deal' and, more generally, the political importance given to nuclear energy. The Manmohan Singh government has made an expansion in nuclear energy capacity the focal point of state policy. In 2008, Singh even went so far as to risk a vote of no confidence over the US–India deal. Yet again, in 2010, an entire session of Parliament was devoted to a bill that allowed for financial liability for nuclear accidents to be channelled to operators, neglecting many other pressing matters.

In the debate over the contentious US–India deal, various political leaders and officials of the Department of Atomic Energy (DAE) made an eloquent case for the importance of nuclear power to India. The most forceful of these arguments is that India's growing energy demand just cannot be met without nuclear power. This was an important theme in Singh's first statement (2005) in Parliament in July after signing the joint statement with President George W. Bush:

> Energy is a crucial input to propel our economic growth. We have assessed our long-term energy resources and it is clear that nuclear power has to play an increasing role in our electricity generation plans. While our indigenous nuclear power programme based on domestic resources and national technological capabilities would continue to grow, there is clearly an urgent necessity for us to enhance nuclear power production rapidly. Our desire is to attain energy security to enable us to leapfrog stages of economic development obtained at the least possible cost. For this purpose, it would be very useful if we can access nuclear fuel as well as nuclear reactors from the international market.

Shortly thereafter, the energy security idea was fleshed out by the DAE through an exercise that involved projecting future electricity demand and supply. On the basis of this exercise, Atomic Energy Commission (AEC) Chairman Anil Kakodkar stated at the Indian Academy of Sciences, Bangalore, that India would face a shortfall of 412 GW by 2050 (Kakodkar 2008, 13). The only way, according to him, to deal with this was to import nuclear reactors. If the deal went through, Kakodkar claimed, the deficit would be 'practically wiped out in 2050'.

Even environmental benefits from the use of nuclear power have been claimed to promote its desirability. As with energy security, these benefits have been quantified by invoking the spectre of climate change. Speaking at a conference on 'Nuclear Power for the 21st Century' in Paris, Kakodkar (2005) put it thus:

> The Indian population corresponds to one-sixth of world population. However, the carbon dioxide emission from India is only around 4 per cent of the global emissions. On the basis of current energy mix and the present-day technologies for electricity production, the CO_2 emission from India alone could become as much as half of the present level of global emission in a few decades from now. A larger share of nuclear power in India beyond what would be realized through indigenous efforts would, in principle, contribute to further avoidance of CO_2 emission which otherwise would be inevitable. (14)

Ironically, the most comprehensive expression of this argument is in an advertisement put out by the ministry of petroleum and natural gas in July 2008. Published in several leading English-language newspapers, this advertisement showed a smiling Manmohan Singh and United Progressive Alliance (UPA) Chairperson Sonia Gandhi waving jubilantly. Below the picture is the assertion: 'Nuclear energy is the most efficient, environmentally cleanest and safe source of energy. It produces more energy than any other source and is replenishable.'

An altogether different theme was articulated by Singh when he stated: 'There is today talk the world over of a nuclear renaissance and we cannot afford to miss the bus or lag behind these global developments' (Bhatt 2007). The danger, in the eyes of the prime minister, was, therefore, that of missing out on a technological opportunity.

Going by these statements, India's nuclear programme is an absolute necessity for the country's technological, economic and social development. It is also desirable on environmental grounds, not just for India but for the world as a whole. While the programme is already on the right track, a little bit of help from foreign countries and unremitting domestic political commitment would allow it to become one of the major sources of energy for the country.

On the face of it, there is much evidential basis for these arguments. Fossil fuels, including coal, are, by their nature, limited. Though fossil fuels are used during processes such as mining and processing uranium, the transport of fuel and the construction of reactors, nuclear power does indeed constitute a relatively low carbon source of electricity.[2] There is indeed *talk* of a nuclear renaissance, though the reality of such a renaissance is disputed (see, for example, Squassoni 2009).

Does this mean that those who are promoting nuclear power are right and that the DAE is indeed going to be able to expand nuclear generation capacity a hundredfold over the next four decades? This query makes apparent the mismatch between the arguments that have been in circulation and the question of feasibility, the answer to which we are seeking. While the Indian nuclear establishment's arguments *might* provide a case for rapidly increasing the nuclear power capacity, they do not in any way lend support to the supposition that it *can* increase rapidly.

THE IMPORTANCE OF HISTORY

The larger problem is that the proponents of these arguments about the potential role of nuclear power have chosen to don historical blinders and that, except for portraying the nuclear programme as a great national technological achievement, there has so far been no careful and analytical examination of the experience of nuclear power. Such an examination—as we show in this book—makes it clear that the likelihood of a rapid expansion of nuclear power is very dim. It also suggests that there are many undesirable consequences that flow from developing nuclear power on a large scale or quickly. And, finally, to close the circle, if nuclear power cannot expand rapidly, then, the arguments about its providing energy security and being a significant option for mitigating climate change become invalid, especially if the achieved expansion comes at the cost of investment in other potential solutions to these concerns.

When viewed from a historical perspective, what is striking about the arguments raised by the proponents of nuclear power is that, except for the climate argument, none of them are novel. One is reminded of the remakes of Hindi movies like *Don* and *Devdas*: the new versions differ in style and presentation, but the story is essentially the same. In 1955, for example, Homi Bhabha, the founder of India's nuclear programme, stated at the First Conference on the Peaceful Uses of Atomic Energy held in Geneva: '*We ... come to the inescapable conclusions that the resources of hydroelectric power and conventional fuels in India are insufficient to enable it to reach a standard of living equivalent to the present U.S. level*' (Bhabha 1955, 107) (emphasis in original).[3] Now too, as then, the energy security ideal is raised in the context of an ever-growing energy demand and an assumption that these demands have to be met, and met through national resources. Note also Bhabha's invocation of only two sources of power—hydroelectric and conventional fuels, which meant coal. Solar power, Bhabha had to admit, was plentiful, but he ruled it out as uneconomic.

The second theme seen in current arguments was not common then, for the environmental consequences of energy production had not become an arena of mainstream concern. The third theme—keeping up with the West—was laid out by Nehru in graphic terms while inaugurating India's first nuclear reactor in 1957: 'Just as the industrial revolution went ahead whether people liked it or not, so this atomic revolution has something inevitable about it. Either you go ahead with it, or others go ahead and you fall back and gradually drag yourself in their trail' (Nehru 1958a, 505). Note the strong similarity between Nehru's invocation of the atomic revolution and Singh's invocation of the nuclear renaissance.

Other tropes have also persisted: about nuclear power being necessary not only for the narrow idea of energy security but also for the broader idea of progress. While laying the foundation stone for a coal power plant in Jhajjar, Sonia Gandhi explained the same idea by arguing that electricity was required for development and that the nuclear deal was required for electricity. She then went on to label opponents of the deal 'enemies of progress and development' (Raju 2009, 1).

The result of such convictions has been that the nuclear power programme has always had the political and financial backing of leaders at the highest levels. Indeed, they have often taken pride in how staunchly they have supported nuclear energy. Speaking in the Lok Sabha, Nehru said: 'In August 1954 [when the DAE was started], I think we spent about a crore of rupees on atomic energy work here. Two years later, that is, in the current year, we are spending twelve times that amount. Money is not much of a test, but still it sometimes helps us to judge how much we are doing' (Nehru 1958b, 515).

That is not to say that there was ever a complete consensus on the subject of nuclear power. In 1954, for example, freedom fighter and Congress leader C. Rajagopalachari argued that nuclear power was 'comparable to a hypothetical case of using the thunderbolt to cook our breakfast', because of the 'terrible character of the risks necessarily attached to this industry' (Guha 2004, 53). He also presciently foresaw that the nuclear production process 'totally disregards the rights of those that do not in any way benefit from the enterprises'. Likewise D.D. Kosambi, the brilliant mathematician and historian, 'repeatedly articulated his vision of solar energy as most appropriate for a developing country like India'; partly due to this articulation, his contract with the Tata Institute of Fundamental Research (TIFR) was not extended in 1962 (Kosambi 2008, 36). The director of the institute at that time was Bhabha. Kosambi's insight—'whether or not an alternate technology is viable is not only a technical question, but also a political and organizational question' (Monteiro 2008, 107)—is also a partial explanation for the difference in the capacities of solar and nuclear power today.

But these voices did not command the power held by those favouring nuclear power. At the time of Nehru's speech, the nuclear establishment had produced no electricity, and the only justification that could be offered in support of the ever-increasing funding was its glorious projections of nuclear power capacities to be built in the future. Over the years, these projections were passed off as certainties, with no attention being paid to the uncertain character of the assumptions underlying them. For example, Bhabha (1964) stated: ‘There is little doubt that before the end of the century, atomic energy will be producing a substantial part of the power in India, and therefore practically all the addition to our power generation will come from it at that time.’ Nearly a decade later, AEC Chairman Homi Sethna (1972, 40) was more quantitative about the same, predicting that India would have 43,000 MW of nuclear generating capacity by 2000.

Projecting future nuclear capacity has always been easy. Translating those forecasts into reality, however, proved impossible, and the installed capacity in 2000 was only 2720 MW. Understanding the reasons for this enormous gap between achievements and projections is crucial for judging whether the setting up of hundreds of GW of nuclear power capacity by mid-century is plausible.

A BRIEF SUMMARY OF THE FINDINGS

Posing these questions is, of course, easier than answering them, especially if one is looking at basing one’s analysis on factual information. An example might elucidate the problems involved. As described in later chapters, the DAE’s plans for expanding nuclear power in the country involve building a large number of a special kind of nuclear reactor called the fast breeder reactor (for a brief description see Appendix 1). These reactors comprise over 90 per cent of the nuclear capacity by mid-century in DAE projections. Examining the feasibility and desirability of these plans is therefore important. The first of these is the prototype fast breeder reactor (PFBR) being constructed in Kalpakkam near Chennai since 2004. Experience around the world has shown that breeder reactors are very expensive, this being one of the factors in the decision taken by many countries to effectively shut down their breeder programmes (IPFM 2010a).

When the construction of the PFBR commenced, my former colleague J.Y. Suchitra and I started looking at how much electricity from the PFBR might cost. The cost of electricity from it would depend, inter alia, on the construction cost of the reactor, the cost of fuelling it with the special mixture of plutonium and uranium that the reactor is designed to use, and the cost of producing the plutonium required. Looking through the large corpus of literature put out by the DAE, we could find stray details here and there, such as the ratio of plutonium to uranium, the amount of plutonium required in the beginning and the intervals between refuelling of the reactor. But, apart from an estimate of the construction cost of the PFBR, there was no economic data.

We then decided to use the Right to Information Act that had just been passed, in 2005, and sent a series of petitions to various units of the DAE, requesting economic information pertaining to the PFBR. The data we requested included the 'cost of fabricating each fuel pin for core and blanket fuel assemblies', the 'cost of reprocessing spent fuel (per unit quantity)', and the 'cost of removing americium from plutonium before fuel fabrication (per unit quantity)'. Practically all our requests were denied, using Section 8(I)(a) of the RTI Act, on the grounds that the disclosure of such information would 'prejudicially affect the sovereignty and integrity of India, the security, strategic, scientific or economic interests of the State, relation with foreign State or lead to incitement of an offence'.

We appealed against this denial, arguing that this was a gross misuse of the provision. We pointed out that we had merely asked for how much money had been, or was projected to be, spent on various activities pertaining to the reactor. We had deliberately not asked, for example, about how much fissile material was used in the PFBR or where such materials were stored. Again, the response quoted Section 8(I)(a) of the RTI Act, adding that 'it is felt that the information you have requested falls within the above definition and therefore, BHAVINI [Bharatiya Nabhikiya Vidyut Nigam, the public sector company set up to construct the PFBR] will have no obligation to give the information requested to anyone' (Ananth 2006b).

Not being satisfied with this response, we appealed further to the Central Information Commission. At the hearing, the members of the Indira Gandhi Centre for Atomic Research (IGCAR) and BHAVINI argued that information regarding the cost concerning the fuel cycle would reveal the type of technology which was being used, and which was of vital strategic and scientific value and, therefore, could not be disclosed. We pointed out that such data was important to determine the cost of electricity generation and that, based on data from other countries, there was good reason to believe that these cost components could constitute even up to half of the total cost. Therefore, it was important to include these cost elements in estimating electricity generation costs at the PFBR. The chief information commissioner agreed that 'the objective of appellant Ms. Suchitra J.Y. in seeking the information is clearly with the sincere objective to see that fuel costs are controlled … [and] is therefore an issue in the public interest. However, the disclosure of this information can have unforeseen ramifications because of the sensitivity in the nature of the project on which the information is sought' (CIC 2007).

We then had no choice but to base our analysis on standard international values, mostly based on experience in the US and Europe, for these quantities of interest. As described in chapter 6, our analysis showed that electricity generated at the PFBR would be significantly more expensive than electricity produced at the heavy water reactors that the DAE continues to construct. Only if uranium costs went up by a factor of nearly seven would the two be competitive. This was unlikely to happen for several decades at the very least. Further, as chapter 2 describes, the DAE's only operating breeder reactor, the fast breeder test reactor (FBTR), has not performed well. This is the case with breeder reactors in other countries, too. If the PFBR does not perform efficiently, that will further increase electricity generation costs. Thus, for the foreseeable future, the breeder reactor will remain expensive.

The same analysis also undercuts the DAE's claim that breeder reactors and the whole three-phase nuclear programme are justified by India's lack of uranium. As uranium cost rises, uranium ores of poorer quality can be extracted economically. Geologists suggest that vastly greater quantities of uranium will become available once such ores are mined. The DAE has been too obsessed with breeder reactors to actually engage with the question of whether and when they would be economical.

Economics is just one of the constraints on the DAE's projections of a vast growth of breeder reactors. A more basic requirement is the plutonium needed to fuel these reactors. As chapter 4 shows, the DAE's projection of breeder capacity in the future does not account carefully for plutonium flows, and the rate of plutonium generation will not suffice to fuel breeder reactors as fast as the DAE envisions (Ramana and Suchitra 2009). When the production and consumption of plutonium are consistently taken into account, the theoretical rate at which reactors can be built decreases by about 60 per cent, even with extremely optimistic assumptions. Thus, the DAE's projections for a fast growth of breeder reactors are not even theoretically, let alone practically, achievable.

What about the desirability of these breeder reactors? This question is addressed in part in chapter 7 which describes how the PFBR is susceptible to a particularly severe type of accident known as a core disruptive accident (CDA), which could lead to a massive release of radioactive substances into the biosphere. The potential for such accidents lies in some physical characteristics of the design of the PFBR (and other breeder reactors). In the case of the PFBR, numerous design choices—often motivated by cost-cutting—have made the reactor more vulnerable to severe accidents and the impacts of such an accident, more catastrophic. An additional reason to be concerned about accidents at the PFBR is the history of accidents, albeit small, at the fast breeder test reactor (see chapter 2).

The bottom line on breeder reactors, therefore, is that they cannot be constructed at the pace envisioned by the DAE, they will be susceptible to catastrophic accidents, and they will produce very expensive electricity.

What about the other types of reactors that the DAE is interested in? Even though the DAE has experience with both pressurized heavy water reactors (PHWRs, the main reactor type deployed by the DAE) and light water reactors (LWRs, albeit of an old design), chapter 2 demonstrates that the DAE's plans do not reflect any sense of learning from the past. First, in practically every site at which reactors—PHWRs or LWRs—were constructed, there were unexpected difficulties that delayed construction. These were not predicted and implementing solutions to these problems took time. Second, problems with the design became apparent only several years after commencement, possibly a decade or more.[4] Sensible planning would, therefore, require the rate of construction to be concomitant with the rate of learning. This is far from the case in the DAE's ambitious plans.

Third, the acquisition of new reactor sites has always been difficult, and is going to become increasingly more contested by local populations in the coming years and decades. All the four sites selected for imported reactors since the Nuclear Suppliers Group (NSG) waiver—Jaitapur in Maharashtra, Kovvada in Andhra Pradesh, Mithi Virdi in Gujarat and Haripur in West Bengal—have seen protest movements emerging. Even more spectacular have been the protracted and intense protests, which exploded in the aftermath of the Fukushima accidents, over the commissioning of the Koodankulam reactors in Tamil Nadu (Ramdas and Ramdas 2011; Kaur

2012). Overwhelming opposition has been recorded consistently at public consultations to discuss environmental impact assessments of nuclear facilities, a necessary step for any project to be accorded an environmental clearance (Ramana and Rao 2010). Two recent examples at the time of this writing were at Gorakhpur in Haryana over the proposed PHWRs and at Rawatbhata in Rajasthan over the proposed Nuclear Fuel Complex (Banerjee and Ramanathan 2012; Sebastian 2012b). Such opposition will likely intensify over the decades as land and other natural resources become subject to competing demands.

Fourth, actual costs of construction inevitably exceed projected costs. This appears to be a result of one of the strategies that the nuclear establishment has adopted in order to continue receiving public funding, namely, to understate reactor costs and then, once construction was under way, to 'revise' them. In the case of Narora, the Comptroller and Auditor General (CAG) of the Government of India concluded that the revision of costs indicated that the project got 'approved on unrealistic cost estimates' and went on to censure the DAE, saying: 'Unrealistic cost estimates and optimistic time schedules make financial allocations and controls less meaningful' (CAG 1988).

This is likely to continue in the future, too. The PFBR being constructed in Kalpakkam has already gone through one increase, from Rs 34.9 billion to Rs 56 billion. For the Jaitapur site in Maharashtra, there were reports that the Nuclear Power Corporation of India Limited (NPCIL) signed a contract with the French company Areva for 7 billion euros (roughly Rs 420 billion) for the first *two* European pressurized reactors (EPRs), including fuel (TNN 2010). Compare this with the current cost estimate of the EPR under construction in France at Flamanville of 6 billion euros (Chaffee 2012, 3). Even if costs are lowered because workers are paid a lot less in India than in France, the Jaitapur cost estimate remains a recipe for future escalation.

Such lowered estimates of construction costs of nuclear reactors are the basis of the DAE's claims about economic competitiveness. These claims and the problems with them are discussed in chapter 6. From early on, the DAE has consistently claimed that nuclear power is economically competitive. In 1957, for example, when the DAE had only just completed its first small research reactor and had no experience with generating electricity, Bhabha announced in New York: 'atomic power as we know it today, is competitive in my country' (G. Smith 1957, F1). The same claim is repeated constantly by the NPCIL; the annual report for 2008–09, for example, says explicitly that nuclear power is 'an economically competitive option' (NPCIL 2009, 56).

However, as documented in [5] NPCIL also resorts to methodologically unsound accounting practices. These include dealing with heavy water costs for PHWRs by treating them as a lease cost instead of as a capital expense.

And, finally, there are the subsidies. Two of the important ones thus far have been the DAE's subsidizing NPCIL by charging low rates for heavy water and taking care of the radioactive spent fuel. As discussed in chapters 4 and 5, these subsidies are by no means small. Such procedures allow the NPCIL to show higher profits over the years while, at the same time, the government keeps allotting larger budgets to the DAE.

When more standard economic accounting practices are used to examine the cost of generating electricity at actually constructed reactors, such as Kaiga I and II, and when they are compared to the corresponding cost at specific coal plants, and one or more of these subsidies are removed, nuclear power turns out to be more expensive for realistic values of various parameters. Nuclear power enthusiasts often claim that future reactors would be cheaper to construct because of the lessons learnt. Historically, however, nuclear construction costs have not reduced significantly. There is, thus, little basis to expect nuclear costs to reduce over time.

Economic costs are not the only arena where there is a difference between what the nuclear establishment claims and what actual experience has been. Safety provides another example. DAE leaders routinely talk about how safety is their highest concern. Speaking at the International Atomic Energy Agency (IAEA) in September 2002, for example, AEC Chairman Anil Kakodkar said (2002, 4), 'Our atomic energy programme has accorded prime position to safety in all its activities'. However, chapter 7 describes why these public pronouncements are not borne out by the DAE's record of accidents, design, institutional structure and decision-making.

Most nuclear facilities in the country have experienced small or large accidents though, fortunately, none of these has been catastrophic. Many of them were caused by inattention to recurring problems or other warnings; to the extent that those responsible for safety have tried to fix them, they have not always been successful. Compounding this state of affairs is an absurd confidence that DAE leaders have publicly expressed—and have likely internalized—in the safety of nuclear facilities in the country. This has often taken the form of asserting that the probability of a nuclear accident in India is zero, something that was frequently heard in the aftermath of Fukushima (Ramana 2012).[6] Such confidence has resulted in the DAE's adopting reactor designs with features that are conducive to accidents or that make reactors incapable of withstanding severe accidents (Kumar and Ramana 2011).

Now, despite all this public talk about nuclear power being safe, all those who manufacture nuclear reactors know that there is always the chance that one of these reactors might undergo a catastrophic accident. That is why they—foreign reactor vendors and the NPCIL—invested so much effort in pushing a nuclear liability bill that was aimed at shielding the manufacturers of nuclear plants from damage claims through the Indian Parliament. For all their apparent confidence about the impossibility of catastrophic accidents, they are unwilling to risk their own financial health on the safety of their plants.

The safety of DAE facilities is important because of the potentially devastating consequences on public health due to radioactive contamination in the event of accidents. Accidents, however, are not the only way that local populations can be exposed to radiation; there are also routine releases of radioactive and other substances from the chain of processes involved in producing nuclear power, and these releases could be hazardous to human health.

There is some evidence from epidemiological studies that populations near some nuclear facilities do exhibit higher levels of certain poor health outcomes, such as congenital malformations. Similar impacts have been recorded in a few cases elsewhere too (see, for example, Shields et al. 1992). Workers, both regular and temporary, have also displayed higher rates of specific untoward health outcomes that can be plausibly linked to working conditions.

Related to the question of occupational and public health is the question of environmental impact. While nuclear power plants and associated facilities emit a smaller quantity of carbon dioxide as compared to fossil fuel plants, they produce nuclear wastes that, for millennia, remain hazardous to health. The challenge of isolating them from human contact creates a need for stewardship that is unprecedented in human history. This fact, more than anything else, perhaps explains why the larger public is sceptical about claims made by the DAE and the government that nuclear power is a clean and environmentally friendly technology.

Despite these public concerns, opposition in various specific settings and multiple failures, how has the nuclear establishment managed to maintain its institutional clout and continued to attract funding and political patronage over all these decades? Some of the important underlying factors are described in chapter 1. They include how the Atomic Energy Commission was instituted and Homi Bhabha's success in establishing the conditions that allowed the DAE to operate largely autonomous of political control. The chapter also briefly covers how the establishment used that autonomy not only to act without accountability but also to develop the wherewithal to design and manufacture nuclear weapons during a period when its ostensible mandate was to explore atomic energy solely for peaceful purposes. At least since 1974—some would date this even to the early 1960s—the ability to promise weapons of mass murder, euphemistically called the nuclear deterrent or credible minimum deterrent, has been one source of political power to the DAE. In this case, too, the DAE has often overstated its capabilities and achievements.

The DAE's power results not from the actual installed electric capacity but from its confident promises—unshaken by past failures—of immensely large quantities of nuclear electricity sometime in the future, and its claim that it is the only credible large-scale source of power. Likewise, in the case of the other promise, the DAE's power is dependent less on the actual amount of weapons-usable fissile material it has produced than on its vaunted ability to make much more of it.

Chapter 1 also shows that, although the DAE has often claimed to be self-reliant, it pursued and obtained numerous technologies from other countries. Reactors, nuclear materials, reactor designs, fuel elements and assorted technologies were obtained from the US, Canada, the UK, and France. Numerous Indian scientists and engineers have been trained there, and researchers have regularly met at international conferences, exchanging technical and other information. In many cases, these external contributions were not acknowledged and the establishment, or its political backers, tried to pass them off as being self-developed.

All this back-and-forth movement of people and technologies was indicative of a larger development: the emergence of an international class of nuclear technologists in the first part of the nuclear age.[7] This had a psychological impetus on nuclear scientists wanting somehow to make amends for their part in building weapons of mass destruction, and trying to get away from the antagonism of the Cold War stand-off between the superpowers. In other words, atomic energy became 'the agent of redemption' (Lindee 1994, 15). David Lilienthal (1963), chair of the US Atomic Energy Commission (USAEC) from 1947 to 1949, explains this feeling:

> The basic cause [of the inflated hopes for atomic energy] was a conviction, and one that I shared fully and tried to inculcate in others, that somehow or the other the discovery that had produced so terrible a weapon had to have an important peaceful use. Such a sentiment is far from ignoble … Everyone … wanted to establish that there is a beneficial use of this great discovery. We were grimly determined to prove that this discovery was not just a weapon. This led, perhaps, to wishful thinking. (109–10)

Among the shared ideas in this group of scientific and technical bureaucrats from different countries was the wishful hope that nuclear power would expand rapidly and prove to be cheap.

Today, again, we see that same wishful hope amongst a wide spectrum of people, many of whom are concerned about the prospect of catastrophic climate change and are hoping that the widespread deployment of nuclear power might have some mitigating effect. This hope, in some measure, has played a role in the re-establishment of nuclear trade between the DAE and international nuclear vendors, through the US–India deal, and the re-emergence of very ambitious plans.

Even though I realize that the US–India nuclear deal and the waiver from the Nuclear Suppliers Group might be an important landmark in the history of nuclear power in the country, I have deliberately relegated a discussion of the details of the agreement and its evolution to Appendix 2. To do justice to the elaborate and involved debates in India and in the United States, the diplomatic games that the two countries played in cities around the world and the political and bureaucratic battles within India would require a whole book. This is not that book. The focus of this book is on what has been materially accomplished and inflicted by the nuclear establishment so far. This history, however, tells us that the deal may not be, as has been argued by its proponents, a turning point in the saga of nuclear power in the country. For various reasons outlined in this book, despite the deal, nuclear power is unlikely to become an important source of energy in India.

The DAE's ability to import reactors is not going to help it overcome most of the challenges it has faced or will face. Many of these challenges are only going to intensify. New challenges too will arise. An example that has drawn limited attention in the public is that of the DAE's difficulties in getting and retaining skilled personnel in recent years. As the chairman of the AEC explained in a 2007 interview with *Outlook* magazine: 'The DAE has been facing the problem for some time now [and] a sizeable number of its nuclear scientists and engineers have left the department. This is primarily because of the private sector … the salaries are much higher …' (D. Dasgupta 2007, 16).

Experience elsewhere also confirms this prognosis. Barring exceptional cases like Iran, all countries which have signed the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), that is, just about every state except India, Pakistan, Israel and North Korea, have been permitted by the Nuclear Suppliers Group to purchase nuclear technology. Nevertheless, in most of them, nuclear power has not developed into a major source of power. As with the DAE, nuclear establishments in many countries have made lofty predictions about the growth of nuclear power. None of these has materialized (IPFM 2007; von Hippel 2010). The case of France, which has nuclear power contributing roughly three-quarters of its electricity, is exceptional, and will likely remain that way.[8] Even in France, there is strong public pressure following the Fukushima accidents to reduce the share of nuclear electricity, and this pressure was a contributor to the success of the Socialist Party, which promised reduced reliance on nuclear power, in the 2012 elections.

MOTIVATIONS

This book is an attempt to assess the success or failure of the nuclear programme according to the terms it set itself. Rather than deal with these topics in the abstract, I focus on the concrete: on specific facilities, the technologies used, the materials involved, the environmental and health impacts of nuclear facilities, and the economic performance of reactors that have been built and are being constructed. In their comparative survey of nuclear power programmes in several countries, scholars John Byrne and Steve Hoffman have noted that nuclear technology 'continues to be evaluated in the "future tense", that is, in terms of what it will bring rather than what it has already wrought or what it requires from society to maintain operation' (Byrne and Hoffman 1996, 12). This future-oriented tendency has also dominated discussion of nuclear power in India; this book will hopefully provide a corrective.

Over a decade ago, in his scholarly volume on the Indian nuclear weapons programme, George Perkovich pointed out that the 'absence of an adequately detailed narrative of the Indian nuclear programme's evolution … has impaired the Indian polity's capacity to debate with adequate knowledge what has been done in the nuclear field, by whom, for what reasons, and at what costs' (Perkovich 1999, 11). In a similar manner, public debate over the vision of a nuclear future painted by the DAE and political leaders has been impaired by the absence of a detailed narrative of the nuclear energy programme's evolution. Thus, though there has been much debate over this question in the last few years, it has not been a particularly informed one. This has been exacerbated due to the near monopolization of technical knowledge about nuclear issues by the DAE and its associated institutions.

The aim of my exercise at the very minimum is to deepen the debate about whether India should indeed embark on a massive nuclear programme. I have tried to do so by uncovering, collating and presenting technical and historical information and analysing it. In various cases, I have also elaborated on the process through which the conclusions have been arrived at so as to enable others to retrace these steps. Accordingly, I have tried to make my assumptions and methodologies as transparent as possible. If not in this book, references to my other published works as well as many other sources of information have been provided to enable the interested reader to pursue the subject further.

There is a small set of books on nuclear power in India to which this adds. The best of them is nearly three decades old (Hart 1983), and much has changed since then. Unfortunately, later books have tended not to do their own assessments.[9] The DAE has produced an official history on the occasion of its fiftieth anniversary (Sundaram, Krishnan, and Iyengar 1998), and a couple of retired DAE leaders have produced their biographical accounts and collections of essays (Ramanna 1991; M.R. Srinivasan 2002; Iyengar 2009). In addition to all these, the DAE and its attendant institutions have put out reports, brochures and other publicity material in industrial quantities. For the most part, these follow a ‘sanitized official narrative of scientific and peaceful progress’ (Abraham 1998, 4), which offers little basis for answering questions about whether nuclear power can or should expand significantly.

The presence of this corpus from the nuclear establishment is one reason why this book has not dealt much with what might be considered by some to be the technological triumphs of the DAE. There is no dearth of accolades for the DAE in the media. Just about every event that is to be expected during the normal functioning of an organization concerned with producing nuclear power, be it installing a safety vessel in a reactor or completing some repair work, is tom-tommed loudly, not just by the nuclear establishment itself but also by political leaders. Is it really necessary to repeat that?

Further, this account tries to evaluate the nuclear establishment’s assertions on its own terms. These include projections of how much electricity they would provide, claims about costs, safety, environmental impact, and so on. Unfortunately, these assertions are mostly unfounded. Therefore, this book or, for that matter, any honest account of the history of nuclear power in India would necessarily appear to be biased against the nuclear establishment. In a sense, the nuclear establishment has but itself to blame. It could, for example, have made modest claims and accepted that it was not foolproof. Then, it would have been harder to mount criticism. By projecting itself as an agency that is superior in all respects, it has just set itself up for failure.

For the most part, the basis for the various pieces of analysis in this book has been factual data. Ultimately, in most cases, the only authentic source of data is the establishment itself. These data are not conveniently available, even if they are not held secret. One further purpose of this book, therefore, is simply to put together a large amount of data on the nuclear programme. This should be of interest even to people not interested in answering questions about the future of nuclear power in India but in what it has wrought so far.

In the data published by the DAE, or other government agencies, one finds that much is lacking. Even standard sources of data, such as expenditure budgets of the Central government, and performance budgets and annual reports of the DAE, tend to confound the researcher in many ways. During the research that my collaborators and I have carried out, we have found that data are not consistent across the years,[10] heads of demand and expenditure are left unexplained, data on some facilities are simply not provided at all, some line items appear and disappear over the years, and data get aggregated in ways that hide the specific expenditures. In the case of most nuclear facilities (the exception is reactors because their electricity generation is publicly known), the level of performance (production figures, throughputs) is never revealed. The reports of the Atomic Energy Regulatory Board (AERB) are more useful, but they do not publish the physical quantities of radionuclides released. Instead, releases are reported as fractions of something called permissible limits, without telling us what these limits are. This means that one cannot independently calculate the radiation doses to which the inhabitants of areas near these facilities might be exposed.

Statements in these reports have to be taken with a pinch of salt and, sometimes, this becomes evident from other pieces of information found in their own documents. For example, in the 2001 DAE annual report, as part of its claim that the ‘performance and safety record’ of all the operating heavy water plants ‘was very good’, the DAE mentions that the plant at Talcher completed more than ‘6.44 million man-hours of continuous operation … without any reportable accident’ (DAE 2001). But, just a few sentences later, it also mentions that ‘Operation of the Heavy Water Plant at Talcher remained suspended due to closure of operation of the fertilizer plant of the Fertilizer Corporation of India on which the plant depends for feed stock and other inputs.' Accidents are generally not possible when production at a facility has been suspended. *Suppressio veri, suggestio falsi.*

Finally, of course, there is the problem of the DAE's history of secrecy and refusal to be transparent (Ramana 2009a). A concrete illustration described earlier was our attempt to obtain cost data on the PFBR through the RTI Act. The reason for DAE's denial was probably that, by giving information of this sort, a precedent might be set for people to challenge the DAE's secrecy on a number of other issues (Suchitra and Ramana 2007). As Noam Chomsky (2010) argued in the context of the WikiLeaks release of diplomatic cables, 'one of the major reasons for government secrecy is to protect the government from its own population'. Such secrecy is detrimental to democratic debate.

Let us now begin examining nuclear power in India with the history of the programme and its antecedents.

1

History

Those who cannot remember the past are condemned to repeat it.

—George Santayana

In 1938, two of India's prominent scientists, C.V. Raman and Meghnad Saha, sent a student each to the West to be trained in nuclear physics (Phalkey 2007, 51). Raman's student, R.S. Krishnan, went to the Cavendish Laboratory at the University of Cambridge, UK, while Saha's student, B.D. Nag Chowdhury, went to the Radiation Laboratory, University of California, Berkeley, USA. A third Indian, only slightly older than Krishnan and Nag Chowdhury, was already at Cambridge and making his mark in the world of quantum and nuclear physics. Homi Bhabha had been awarded the prestigious Isaac Newton Studentship in 1934 and, along with Walter Heitler, had written an important paper on cosmic rays in 1937.

Both Raman and Saha were profoundly fascinated by nuclear physics. Though he himself never worked on the subject in any significant fashion, Raman was to declare publicly that nuclear physics was *the* research 'problem of the time'. The statement reflected the mood in the wider physics community, and nuclear physics was an arena of intense activity in the 1930s.

In 1932, three discoveries had transformed the field: James Chadwick's discovery of the neutron, Carl Anderson's identification of the positron—the positively charged counterpart of the electron—and John Cockcroft and Ernest Walton's use of a particle accelerator to perform the first artificial disintegration of the atomic nucleus (Hughes 2000). The discoveries significantly impacted the understanding and eventual application of the spontaneous disintegration of an atomic nucleus, that is, radioactivity.

In 1934, Irène and Frédéric Joliot-Curie realized the alchemist's dream of turning one element into another, and created radioactive nitrogen and phosphorus by bombarding boron and aluminium with alpha particles respectively. Soon afterwards, Enrico Fermi and his group showed that the same phenomenon could be more efficiently achieved by neutron bombardment, especially if the neutrons were slowed down. In 1938, Otto Hahn, Fritz Strassmann and Lise Meitner discovered that heavy atomic nuclei could split into two or more parts, thereby liberating energy, a process they termed fission.

The idea of energy being generated through the decay of the nucleus was already in the air, if only vaguely. As early as 1908, Frederick Soddy who, along with Ernest Rutherford, had discovered that radioactivity was caused by the decay of elements, such as radium, had prophesied: 'The energy in a ton of uranium would be sufficient to light London for a year … if only it were under our control and could be harnessed to do the world's work in the same way as the stored energy in coal has been harnessed and controlled' (Soddy 1909, 229).[1] But uranium was not yet under the control of scientists even in the 1930s, and could not be 'shattered at will', the condition that led Albert Einstein to remark in 1932 that there was 'not the slightest indication that nuclear energy will ever be obtainable'.

The first few decades of the twentieth century also saw a flourishing of science in the Indian subcontinent.[2] C.V. Raman had won the 1930 Nobel Prize in Physics, and Meghnad Saha had been nominated for one. Starting with the mathematician S. Ramanujan in 1918, ten scientists had been elected as Fellows of the Royal Society of Britain before India became independent in 1947.

Radioactivity as a phenomenon had also attracted the attention of some early Indian scientists, including Ruchi Ram Sahni of the Government College, Lahore, who studied under Ernest Rutherford at the University of Manchester (1912–14); Satyendra Nath Bose from Dhaka University who worked with Marie Curie in Paris (1924–25); and Rajendra Lal De, again from Dhaka University, who worked with Marie Curie and with Otto Hahn in Berlin (Phalkey 2007, 23). With the growth of nuclear physics as a prominent focus of research activity, it is not surprising that Indian scientists were a part of that field as well.

Homi Bhabha was the first of the three physicists to return to India. Though he had achieved some fame for his work on cosmic rays, he did not have a permanent position at Cambridge (Abraham 1998, 41). His application for a reader's position at the University of Liverpool had been turned down, but he managed to obtain a grant to work in the laboratory of P.M.S. Blackett in Manchester. But before taking up that position, he made a trip to India in 1939 and found himself unable to return to England as the Second World War broke out.

Bhabha took up a position at the Indian Institute of Science (IISc), Bangalore, but for a while he seems to have considered it a temporary arrangement, desiring to go back to England as soon as possible. His papers from 1940, for example, stated: 'at present at the Department of Physics, Indian Institute of Science, Bangalore' (Mian 1998, 5). In Bangalore, Bhabha worked on various assorted topics related to the physics of cosmic rays and elementary particles. It was during this period that he was awarded the first of his grants to pursue his research interests by the Sir Dorabji Tata Trust, a philanthropic organization. The choice may have had something to do with family connections, for Bhabha's father's sister was married to Sir Dorab J. Tata.

Bhabha was still in Bangalore when another of the three physicists, R.S. Krishnan, joined the same institution. Krishnan had just been awarded his doctoral degree in 1941 for his thesis, 'Investigations in Artificial Radioactivity' (Phalkey 2007, 152). During his stint at the Cavendish Laboratory, Krishnan claimed several discoveries and published twelve papers, all dealing with the bombardment of heavy elements, including uranium and thorium. In March 1942, Krishnan submitted a proposal entitled 'A Scheme for Power Production from Uranium Fission' to the Council of the Indian Institute of Science, but withdrew the proposal after consultation with Raman and the director of the institute (Phalkey 2007, 162–67). Through this submission, Krishnan became the first person—though largely forgotten—to propose exploiting nuclear energy in India. He forwarded another proposal in June 1945 to establish a radiation laboratory, only to have it rejected.

The nuclear explosions over Hiroshima and Nagasaki prompted Krishnan to write an article on atomic energy in *Current Science*, a scientific journal published by the Indian Academy of Sciences, wherein he traced the history of the subject and went on, much in the manner of Soddy, to prophesy: ‘If the tremendous energy released from the atomic explosions is made available to drive machinery, it will bring about an industrial revolution of a far-reaching character.’ There was, however, a difference: Krishnan was altogether more cautious and added: ‘There are obvious difficulties connected with the control of the evolution of atomic energy … it is necessary to emphasize that the prospects of producing cheap atomic power are none too bright’ (R.S. Krishnan 1945, 187).

If he saw obvious technical difficulties with controlling atomic energy, Krishnan encountered significant, although not so obvious, difficulties in establishing a research effort in the subject. In September 1946, he submitted another proposal, this time outlining a plan to build a high-voltage generator that could be used to accelerate subatomic particles. Some months later, after spending time abroad in physics laboratories, Krishnan sent in yet another proposal to purchase equipment for use in nuclear physics research. Despite a lengthy preface by Raman outlining the importance of nuclear research, and ‘the paramount necessity of developing sources of atomic energy by every conceivable method’ that has been felt by ‘all countries’, that proposal too was rejected. That was to be the end of Krishnan’s efforts in atomic energy research.

Saha and Nag Chowdhury did somewhat better and managed at least to institute a research and training programme in nuclear physics in Calcutta. At Berkeley, Nag Chowdhury had worked with Nobel Laureate E.O. Lawrence, the head of the famed Radiation Laboratory and the inventor of the cyclotron, a machine capable of accelerating subatomic particles. The Rad Lab was one of the major centres of wartime nuclear research and Lawrence, an important participant in the Manhattan Project. After completing his PhD, Nag Chowdhury kept in touch with the various scientists associated with the Rad Lab who, in turn, helped procure materials for his projects in India.

Even before Nag Chowdhury returned from Berkeley, Saha busied himself with the business of raising funds for a cyclotron. In contrast with the Bangalore proposals, Saha, in his application to the Sir Dorabji Tata

Trust for funding, stressed the medical benefits of nuclear research. The Tatas were already in the process of establishing a cancer hospital and research centre in Bombay and did grant a sum of Rs 60,000 to Saha and Nag Chowdhury in 1940 (Phalkey 2007, 235).[3] The amount was, however, insufficient to establish a cyclotron and the Calcutta team had to struggle till 1954 before getting the cyclotron to work.

Despite the difficulties with the cyclotron, Saha continued to harbour great ambitions for his institute and actively pursued the possibilities of procuring a 'pile', the term used in the 1940s for nuclear reactors.[4] He sought help from the French physicist Frédéric Joliot-Curie who had organized the construction of 'a successful pile in spite of refusal of English and American authorities to supply uranium and data about [the] construction' (Phalkey 2007, 278). But his efforts to get the necessary information proved unsuccessful, and the reactor was never built.

SUCCESS

In March 1944, after some years in Bangalore, Homi Bhabha wrote a now-famous letter to the Sir Dorabji Tata Trust, requesting funds to set up a research institute (Bhatia 1979; Venkatraman 1994, 113). In the most often quoted part of his letter, Bhabha promised: 'When Nuclear Energy has been successfully applied for power production in say a couple of decades from now, India will not have to look abroad for its experts but will find them ready at hand' (Sethna 1979, 2). But that was not the only promise. Bhabha also argued: 'If much of the applied research done in India today is disappointing and of very inferior quality, it is entirely due to the absence of a sufficient number of outstanding pure research workers who could set the standards of good research and act on the directing boards in an advisory capacity' (Anderson 2010, 105). It is these absences that Bhabha sought to fill using funds from the Tata Trust.

At a meeting held on 14 April 1945, the trustees agreed to Bhabha's request. The minutes of the Trust record: 'After discussion of the financial implications of Dr Bhabha's proposal as embodied in his letter, the Trustees decided to undertake the responsibility. They were of the opinion that this responsibility should be shared from the outset with the Bombay University and the Bombay Government—both in respect of finance and administration' (Lala 1998, 99). The initial Tata grant was Rs 45,000 per year (roughly 3 million in 2011 rupees). While Bombay University did not join in, the Bombay Government gave a grant of Rs 25,000, which was augmented by a grant from the Government of India of Rs 10,000. From then on, the Government of India took on most of the financing.

The timing was propitious—a few months later, in August 1945, the whole world was to learn about the power of the atom from the wholesale destruction of Hiroshima and Nagasaki. To many, Bhabha must have seemed a far-sighted and prophetic scientist, one whose advice ought to be heeded by leaders of an emerging country. There was no stopping him from then on, and Bhabha went on to succeed in the effort that Raman and Saha had failed in: setting up an institute for the investigation of nuclear science and technology.

Being the head of a small research institute was hardly the goal that Bhabha had set himself. As the Tata Institute of Fundamental Research (TIFR) was just being established, he was also reaching out to more powerful people. The most important of them was the man who was to become India's first prime minister, Jawaharlal Nehru. Nehru and Bhabha met for the first time on a ship in 1937 and seem to have hit it off right from the beginning (Lala 1998, 112). This was hardly surprising for they had much in common. Both were born to wealthy parents, had been educated at Cambridge, and were deeply interested in arts and music. Over the years, a deep friendship developed between the two (Chowdhury 2009). As Nehru's daughter Indira Gandhi was to reminisce years later: 'The life of a politician lacks many of those warm moments of sensitivity that other people take for granted in their everyday life … I know that Homi Bhabha opened one such "window" for my father … he always found time for Dr Bhabha, not only because the problems which Dr Bhabha brought were important and he wanted to give them urgent attention, but because he found at the same time it was relaxing and it was an entirely new world' (Lala 1998, 112).

But, more than anything else, the most attractive characteristic about Bhabha as far as Nehru was concerned was that he was a scientist. Scientists were important to him 'because their work enabled his government to refashion India in the image of Nehru's thinking' (Kapur 1994, 225). Addressing the Indian Science Congress in 1938, Nehru emphasized his faith in science saying:

> The application of science is inevitable and unavoidable for all countries and people today. But something more than its application is necessary. It is the scientific approach, the adventurous and yet the critical temper of science, the capacity to change previous conclusions in the face of new evidence, the reliance on observed fact and not on pre-conceived theory—all this is necessary not merely for the application of science, but for life itself and the solution of its many problems (Bhatia 1979, 72).

On another occasion, he said, ‘It is science alone that can solve the problem of hunger and poverty, of insanitation and illiteracy, of superstition and of deadening custom and tradition, of vast resources running to waste, of a rich country inhabited by starving people … Who indeed can afford to ignore science today? … The future belongs to science and to those who make friends with science’ (Morehouse 1985, 1–2). Nehru was not unique, only the best-known example of this sort of thinking.

Thus, Bhabha ‘did not have to … convince people that the specific scientific solutions that he had to offer were precisely what the country needed … audiences were already convinced that science contained the solution to India’s dual problem of economic underdevelopment and political subjugation’ (Abraham 1998, 62). By virtue of being a practitioner of the branch of science most in vogue in the mid-1940s, that is, nuclear science, and with impeccable credentials from the West, Bhabha had an easy path to power.

In addition to his belief in science, Nehru was also a believer in India’s having a planned economy, with the planning component to be dominated by science and industry. An early indication of this emphasis was when the National Planning Committee was formed under his chairmanship in September 1938. Among its fifteen members were five scientists, four industrialists, three economists and a representative of industrial workers. Despite the overwhelming role played by agriculture in India’s economy, especially in those days, there was not one in the committee from that sector (Chakrabarty 1992, 282). One of the members of the committee, the Gandhian economist, J.C. Kumarappa, resigned in protest when faced with the unwillingness of other committee members to give adequate importance to rural development (Sandhu 1993). This pattern was to continue in later years, and Kumarappa remained ‘virtually the only economist to question the centralized and resource-intensive path of development adopted in independent India’ (Guha 2006, 49).

Finally, Nehru realized that the power derived from the atom could be used not just for economic development, but also in a weapon. In a remarkably forthright speech dating back to 1946, he said, ‘As long as the world is constituted as it is, every country will have to devise and use the latest scientific devices for its protection. I have no doubt that India will develop her scientific researches and I hope Indian scientists will use the atomic force for constructive purposes. But if India is threatened she will inevitably try to defend herself by all means at her disposal’ (Norman 1965, 186).

All told, nuclear power offered multiple attractions for nationalist leaders like Nehru. It was advanced science and held the promise of the latest of modern technologies; it claimed to be able to uplift the material conditions of Indians by providing cheap electricity; and finally, albeit reluctantly, it could be used to produce the most destructive weapons that had recently been on display at Hiroshima and Nagasaki. Bhabha, who promised India’s acquisition of this technology, had no trouble therefore getting the patronage of Nehru and other political leaders, and was duly appointed chairman of the newly created Board of Atomic Research, an agency of the Council of Scientific and Industrial Research (CSIR).

Bhabha was unique not in the audacity of his visions for nuclear energy in India but in his ability to successfully meld science with politics, capital with government. He was, to use a concept articulated by many who study the social history of technology, a heterogeneous engineer (Law 1987). A heterogeneous engineer brings together various technical and social elements to create the sense of a need for that technology and carve out a historical and technological trajectory that appears natural, as though it were dependent only on scientific and technological factors, despite the social and political effort necessary to sustain it.

The head of CSIR was yet another ambitious heterogeneous engineer, Shanti Swarup Bhatnagar. Armed with a doctoral degree from the University College London, Bhatnagar was amongst the first Indian scientists to apply his talents to industry. Having achieved success and financial support for his petroleum research, Bhatnagar went on to become the head of the Board of Scientific and Industrial Research, which later metamorphosed into the CSIR in 1942.

Bhatnagar was another beneficiary of Nehru's interest in science and he carved out his own empire. Even before Independence, the CSIR had developed plans for setting up eleven specialized national laboratories; foundation stones of four were laid prior to 15 August 1947 (N. Anand 2005, 305). The CSIR was thus a logical place to start nuclear research in India. Bhatnagar and Bhabha seemed to have shared a good relationship, and Bhatnagar would eventually become one of the members of the Atomic Energy Commission.

But Bhabha's ambitions were bigger. He soon found a way to argue his way out of this set-up and have his own organization to preside over. On 26 April 1948, Bhabha prepared a note to Nehru entitled 'Organisation of Atomic Research in India', in which he recommended that 'The development of atomic energy should be entrusted to a very small and high powered body composed of say, three people with executive power, and answerable directly to the Prime Minister without any intervening link. For brevity, this body may be referred to as the Atomic Energy Commission'. Bhabha's winning argument was that nuclear matters required strict secrecy, which he felt would not be possible under the earlier board, because it was answerable to the CSIR. As Bhabha put it: 'secret matters cannot be dealt with under this organization' (Venkatraman 1994, 145).

SETTING UP THE COMMISSION

Secrecy was also the main point of debate in the Constituent Assembly, the body that wrote the Indian Constitution, as the legislative bill enabling the creation of the Atomic Energy Commission was introduced. The legislative act was 'modeled on Britain's Atomic Energy Act but imposed greater secrecy over research and development than did either the British or the American atomic energy legislation' (Perkovich 1999, 18). Nehru gave two reasons, both somewhat disingenuous, for the imposition of secrecy. 'The advantage of our research would go to others before we even reaped it, and secondly, it would become impossible for us to cooperate with any country which is prepared to cooperate with us in this matter, because it will not be prepared for the results of researches to become public' (Bhatia 1979, 84).

The key criticism of the bill pertained to its secrecy provisions. One member, Krishnamurthy Rao, compared the bill with the British and

American acts and pointed out that the bill did not have mechanisms for oversight, checks and balances as did the US Atomic Energy Act (Abraham 1998, 51). Further, Rao pointed out, in the bill passed in the UK, secrecy was restricted only to defence purposes and asked whether, in India, secrecy would be extended also to research for peaceful purposes. Though it may seem surprising for someone who had spoken so eloquently against nuclear weapons, Nehru had to confess: ‘I do not know how to distinguish the two [peaceful and defence purposes].’ Nehru’s dilemma is clear from his statements while introducing the bill. On the one hand, he said, ‘I think we must develop it for peaceful purposes’ (Abraham 1998, 51). But he went on to add: ‘Of course, if we are compelled as a nation to use it for other purposes, possibly no pious sentiments will stop the nation from using it that way.’

The connection between developing nuclear energy and acquiring the capacity to build nuclear weapons was clear to Nehru as it was to many of the scientists and statesmen of that period. Indeed, it was perhaps more apparent then—in the immediate aftermath of the US bombing of Hiroshima and Nagasaki—than today. In the intervening decades, the nuclear power industry has argued at length that it is possible to divide civilian and military applications of atomic energy neatly and to keep them separate. This was not the case in the mid-1940s, and those developing the Indian nuclear programme assumed implicitly—and correctly—that the facilities constructed and the expertise gained in generating nuclear electricity could be used for military purposes.

If there was only one objection to secrecy in the Constituent Assembly, there were no questions whatsoever about the appropriateness of giving such a high priority to atomic energy. This would seem remarkable considering that the ethos of nuclear technology was entirely opposed to that of Mahatma Gandhi, whose influence at that time must have been considerable. To anyone who subscribed to the Gandhian vision for India’s development, the development of nuclear technology—which was closely linked to weapons of mass destruction and whose purported benefits would flow to the urban elite and heavy industry rather than to the rural masses and small-scale industry—should have been anathema.

But Nehru’s speech eulogizing atomic energy and its importance allowed no doubts to be raised on the matter.

> We are on the verge I think of a tremendous development in some direction of the human race. Consider the past few hundred years of human history: the world developed a new source of power, that is steam—the steam engine and the like—and the industrial age came in. India with all her many virtues did not develop that source of power. *It became a backward country because of that.* The steam age and the industrial age were followed by the electrical age which gradually crept in, and most of us were hardly aware of the change. But enormous new power came in. Now we are facing the atomic age; we are on the verge of it. And this is something infinitely more powerful that either steam or electricity. (Abraham 1998, 28) (Our emphasis)

Thus, in Nehru's mind, the connection between the failure to develop a source of power and *backwardness* was very clear. He mentions no other contributory factors. It should be no surprise that he later termed dams the 'Temples of Modern India'. Given such a preamble, it seems natural, then, that no member in the assembly would want to be seen as keeping India backward by questioning the necessity for nuclear power.

Another explanation for the silence could be the composition of the Constituent Assembly. Those eligible to vote in the elections of the assembly—before Independence and when the Constitution was being formulated—comprised barely 11 per cent of the population of British India and the princely states. In effect, therefore, only people from the upper and middle classes debated and finalized the Indian Constitution. 'The Assembly was the end product of a historical process which had created a certain class of people, largely homogeneous in their conditioning, exposure and thinking' (Varma 1998, 19–20). And, for this class, 'it was Nehru's vision of an awakened India, invulnerable to outside manipulation and moving towards the creation of a modern and industrialized economy … that had a far greater appeal' (Varma 1998, 30).

The high level of support for the AEC's activities translated into ample funding and unique access to political authority. Some weeks after the Constituent Assembly debate, Nehru sent a note to the cabinet to authorize Rs 10 million to be disbursed over a period of four years (Abraham 1998, 60). Even in that note, Nehru emphasized the importance of secrecy and the need to cooperate with foreign countries, all without oversight. He also recommended that the AEC report directly to the Prime Minister's Office (PMO). This was in contrast to most policy matters where the cabinet has the ultimate authority; thus, the nuclear establishment was not subject to standard checks and balances from its very inception.

On other occasions, Nehru evidently felt helpless in the face of the secretive functioning of the AEC. In a revealing 1952 letter to his minister of finance, who had expressed concern about the high costs of the AEC—particularly when it provided so little information to justify its need for money—Nehru said explicitly, ‘The work of the AEC is shrouded in secrecy. I try to keep in touch with it and get reports from time to time … I do not know how else we can proceed in this matter’ (Nehru 1996; Anderson 1999, 26; Anderson 2010, 199–200).

THE CHALLENGE FROM SAHA

This excessive attention and funding given to the AEC did draw public criticism, most prominently from Meghnad Saha, who was almost completely excluded from atomic energy decision-making. In addition to his background in nuclear technology, Saha was also intimately familiar with discussions and formulations of science policy. As early as 1938, Subash Chandra Bose, the then president of the Indian National Congress, had invited Saha to join the National Planning Committee. Saha became the chairman of the Power and Fuel Subcommittee as well as a member of the River Transport and Irrigation subcommittees (Anderson 2010, 84). Prior to that, Saha had started the influential science and science policy journal *Science and Culture*, and used it to espouse his views on science planning.

Saha and Bhabha differed in their notions about the goals of science and technology, and the means for achieving these goals. Saha ‘emphasized judicious and equitable distribution and advocated participatory democracy even in engineering projects that involve highly technical information’ (Sur 2002, 95). But such an approach was not the one adopted in India after independence. Despite the deep political roots in the Indian nationalist movement that Saha had, Bhabha’s more elitist approach prevailed over Saha’s more open and democratically disposed approach (Satyamurthy 1984, 110).

The emphasis on technical and other expertise was a hallmark of policymaking in the 1950s, during which period ‘professional economists and technocrats came to fill the entire space of public discussion about India’s progress’ (Khilnani 1997, 85). There was little space for democratic debate and decision-making. Nowhere was this more apparent than in the

Planning Commission, ‘the exclusive theatre where economic policy was formulated’. Within this set-up, economic policymaking ‘was removed from parliament and the cabinet—they were now merely informed of decisions taken by the small cohort of experts … The Planning Commission’s work relied on being insulated from wider public deliberation about India’s future’ (Khilnani 1997, 85–86).

Saha and Bhabha also differed in their views on how to go about establishing nuclear science and technology in India. On 25 January 1947, Bhabha wrote to Saha saying that India needed to ‘import one or two really first-class men from abroad for a limited period’ to give ‘experimental work in Nuclear Physics and Cosmic rays a great fillip’ (Sur 2011, 128). Saha, on the other hand, insisted that India first address the ‘dearth of good mechanics, laboratory men’ and lack of engineering and manufacturing firms to be successful in nuclear research (Sur 2011, 128). He wanted India to first expand its industrial base before embarking on the development of nuclear energy, and opposed the creation of the Atomic Energy Commission. Given these views, it is not surprising that he was not appointed to the Commission and was excluded from nuclear decision-making.

Excluding and ignoring Saha, however, was not easy. In 1952, he contested the Lok Sabha elections from the Calcutta north-west constituency and won. As a parliamentarian, he forced debate on the activities of the AEC, focusing especially on its failure to live up to its promises. In May 1954, on the floor of the Lok Sabha, he reminded everyone that in 1948 it had been announced that the AEC was ‘going to set up a nuclear reactor within five years’. He then went on to ask: ‘This is 1954 and [the] nuclear reactor has not been set up … I do not know how long it will take us to make good this proposal’ (Abraham 1997, 2139). This was impossible to ignore and Nehru agreed to hold a special conference on atomic energy inviting scientists from around the country.

The conference on ‘The Development of Atomic Energy for Peaceful Purposes in India’ was held at the National Physical Laboratory (NPL) in Delhi on 26 and 27 November 1954. The AEC used the occasion to present numerous papers on various aspects of nuclear technology and its promise, all talking in general terms about the value and importance of atomic energy for development (Abraham 1998, 75). To all, except the converted, it must have been obvious that nothing had really been done in India. A telling example of this was the retort from the physicist Satyendra Nath Bose to a paper by Homi Sethna on waste disposal: ‘What waste do you have to dispose of except night soil?’ (Ramanna 1991, 61).

The purpose of the conference, however, was not really to question the AEC; it was to allow the AEC to assert its legitimacy in a very public fashion, to silence those questioning its credibility. This was clear from the agenda of the conference, the people invited, and those who were selected to speak. Practically all the presentations were by people associated with the nuclear establishment. Saha presented one paper on the second day of the conference on ‘Considerations in the Choice and Design of Reactors’ (Abraham 1998, 75). The very marginality of the topic indicates the limited impact of his intervention.

Further, the choice of location itself made it very difficult to challenge the AEC. K.S. Krishnan, the director of NPL, was one of the three founding members of the AEC and was chosen to sum up the proceedings of the conference. Not surprisingly, his summary interpreted the discussions in a way that favoured the AEC. In the words of Raja Ramanna, who went on to head the AEC some decades later, Krishnan would ‘save the day for us [the AEC]’ (Ramanna 1991, 61). In all, the conference served as ‘confirmation of the atomic scientists’ dominance over other scientists and state agencies’ (Abraham 1997, 2140).

DREAM SEQUENCES

At the 1954 conference, the AEC resorted to what has now become one of its standard responses to criticism: painting a glorious future with impressive projections of massive quantities of nuclear electricity. In his speech, Bhabha outlined the much-written-about three-stage or three-phase nuclear programme (Mirchandani and Namboodiri 1981, 28–29). The first stage of the strategy involves the use of uranium to fuel heavy water reactors (see Appendix 1 on nuclear reactor types), followed by reprocessing the irradiated spent fuel to extract plutonium (Bhabha and Prasad 1958, 93–94). In the second stage, the accumulated plutonium stockpile is used in the nuclear cores of fast breeder reactors (see Appendix 1 on nuclear reactor types). These nuclear cores could be surrounded by a blanket of uranium, to produce more plutonium; if the blanket were to use thorium, it would produce uranium-233.[5] In order to ensure that there was adequate plutonium to fuel these second-stage breeder reactors, a sufficiently large fleet of such breeder reactors with uranium blankets would have to be commissioned before thorium blankets were introduced. The third stage involves breeder reactors using uranium-233 in their cores and thorium in their blankets. The primary goal was to base the growth of nuclear power on thorium—of which India had plenty—rather than uranium, which is relatively scarce.

Technologically, it is not surprising that Bhabha would base his idea of expanding nuclear power on breeder reactors. The essential principle behind the breeder reactor—that one could produce more fissionable fuel than would be consumed[6]—had been recognized by physicists as early as 1943. The first concepts were developed by Leo Szilard who was responding to concerns shared by his colleagues, who were engaged in developing the first nuclear bomb, that uranium would be scarce (von Hippel and Jones 1997, 48). As a physicist, Bhabha could not have been but beguiled by the idea that one could produce more fissile material than was put in.

In early 1953, just a year before the 1954 conference where the three-phase strategy was announced, tests in the US at the Experimental Breeder Reactor-1 (EBR-1)—the world’s first reactor to produce enough power to light up the building it was housed in—showed that the reactor was creating as much nuclear fuel as it burned.

The Soviet Union, the other major nuclear power of that time, was not to be left behind. In 1948, around the same time as the construction of EBR-1 was beginning, Aleksandr Ilich Leipunskii, a well-known Soviet physicist who managed to escape the Stalinist Purges, had begun the breeder reactor programme (Josephson 2000, 50). In his pitch to the USSR government, Leipunskii simply presumed that there would be a deficit of uranium resources for the future development of the nuclear industry. Taken in by the rosy promises of a nuclear-powered future, the government decided to start a breeder programme with Leipunskii as the scientific head. Within ten years, three pilot-scale fast neutron reactors had been constructed.[7]

The idea of a phased programme involving different kinds of reactors was also proposed by many others. For example, in October 1954, at the National Industrial Conference Board in New York, François Perrin, the head of the French Atomic Energy Commission (CEA), had spoken about the five-year plan for developing nuclear energy in France (National Industrial Conference Board 1954; Bhatia 1979, 97). Perrin argued that France will 'have to use for power production both primary reactors [using natural or slightly enriched uranium] and secondary breeder reactors [fast neutron plutonium reactors] … in the slightly more distant future … this second type of reactor … may be replaced by slow neutron breeders using thorium and uranium-233. We have considered this last possibility very seriously since the discovery of large deposits of thorium ores in Madagascar' (Perrin 1955, 93).[8]

While physicists in half a dozen countries have been enticed by breeding, none of these countries has managed to build a successful breeder programme. The elaborate scheme to try and use the thorium reserves in India remains futuristic wishful thinking, despite decades of research effort. The description of the thorium programme from nearly three decades ago, as involving the 'manipulation of untested technology and uncosted investments' still rings true (Pringle and Spigelman 1981, 177). The reactor type that Bhabha used as the basis for his calculations of rapid growth—molten core breeders—were never pursued anywhere. There are no thorium-based breeders in the world. So, there is no empirical basis for the implicit assumption that generating electricity through the use of thorium would be economical. Indeed, technically, because several properties of thorium and uranium-233 make those materials harder to work with as compared to uranium and plutonium, one would expect just the opposite.[9]

No doubts deterred Bhabha, however, and he was to elaborate on the reason for the three-phase programme and the espousal of breeder reactors in 1955 at the historic First Conference on the Peaceful Uses of Atomic Energy held in Geneva. Following in the footsteps of the Atoms for Peace initiative by US President Eisenhower in 1953, the conference was the scene of much Cold War era manoeuvring and an opportunity for countries to exhibit their nuclear wares and woo potential customers (Pringle and Spigelman 1981, 165–78; Bothwell 1988, 212–17). One result of the tussle between the US and the Soviet blocs was the selection of Bhabha, seen as both neutral and carrying adequate scientific weight, as conference president.

If Nehru had offered an indisputable argument for atomic energy in the Constituent Assembly on the grounds that its absence would result in India's backwardness, Bhabha went one step further in his presidential address to the 1955 Geneva conference. He chose to divide all human history into three great epochs:

> The first is marked by the emergence of the early civilizations in the valleys of the Euphrates, the Indus, and the Nile, the second by the industrial revolution, leading to the civilization in which we live, and the third by the discovery of atomic energy and the dawn of the atomic age, which we are just entering. Each epoch marks a change in the energy pattern of society. (Jain 1974, vol. 2, 13)

The parallel with the Marxist conception of different stages of history is striking. But where Karl Marx had thought about relations of production as being the signifier of difference between stages, for Bhabha, it was energy, 'the great prime mover' that 'makes possible life itself', that set apart one stage from another. Having placed energy in this central role, Bhabha went on to argue that 'our presently known reserves of coal and oil are insufficient to enable the under-developed countries of the world … to attain and maintain for long a standard of living equal to that of the industrially most advanced countries'. This, Bhabha said,

> shows the absolute necessity of finding some new sources of energy, *if the light of our civilization is not to be extinguished*, because we have burnt our fuel reserves. It is in this context that we turn to atomic energy for a solution … for the continuation of our civilization and its further development, atomic energy is not merely an aid; it is an *absolute necessity*. (Jain 1974, vol. 2, 14) (Our emphasis)

In other words, those who questioned atomic energy wanted to extinguish the very light of our civilization.[10] Who could possibly want to do that? The image that is created through such statements is one of potentially debilitating energy scarcity, so that any kind of action—constructing expensive reactors, displacing farmers from their lands, and so on—can be justified.

When it came to realizing that dream for India, however, Bhabha had a problem: the country had limited means. At that time, the known deposits of uranium ore in the country 'containing more than 0.1 per cent uranium'—what might be considered reasonably attractive in economic terms—only had 'a total uranium content of roughly 15,000 tonnes'. Bhabha was careful to add that 'much larger quantities of uranium are available in ores of lower concentrations', a qualifier that the DAE subsequently chose to drop. Notwithstanding the caveat, Bhabha (1955) argued that, when used in thermal reactors which exploit only the uranium-235 content, these 'reserves of uranium in India known at present would … only have an energy equivalent of about 315 million tonnes of coal' (107). This was much smaller than the known coal deposits in India at that time. To suggest importing uranium from other countries, especially in the early post-Independence years, would, of course, not do much for the nuclear establishment's claims about being indigenous.

This was the underlying conundrum that led the AEC to propose the three-phase nuclear programme. There was little empirical evidence that the scheme would work. But from that point onward, exaggerated pronouncements based on breeders were to be the bread and butter of the DAE's public relations campaign. For example, on 6 September 1957, speaking in Dublin on the 'Economics of Atomic Power Development in India and the Indian Atomic Energy Programme', Bhabha was to project confidently: 'As far as India is concerned … the best way of obtaining fissionable material appears to be to produce plutonium as a by-product in atomic power stations working on natural uranium … It seems likely that breeder stations may begin to operate by about 1965' (Chaudhuri 1972, 535). All that materialized in 1965 was the formation of a fast reactor section at the Bhabha Atomic Research Centre (BARC) under S.R. Paranjpe which began to try and design a pilot-scale (10 MW) experimental fast reactor (Bhoje 2006, 1). Even that failed and the DAE had to turn to the French Atomic Energy Commission for the design of such a reactor in 1969 (see chapter 2).

INSTITUTIONALIZATION

The challenge from Saha having been met with at the 1954 conference in Delhi, it was time for Bhabha and others to start consolidating their position. One step was to change the status of the nuclear establishment. Though Bhabha had been chairperson of the Atomic Energy Commission since 1948, the AEC, as a ‘commission’, enjoyed only consulting powers to the government. The way to climb up the political power ladder was to become a government department; then Bhabha, as its head, would become Secretary to the Government of India—the highest bureaucratic office in the system. His position was made even more powerful compared to that of other Secretaries because, when the Department of Atomic Energy was set up in 1954, it came under the direct charge of Nehru, who assumed the position of minister of atomic energy (Mirchandani 1968, 5). The DAE, therefore, like the AEC, was not answerable to the cabinet. The same year, the Atomic Energy Establishment, later to be renamed the Bhabha Atomic Research Centre (BARC), was set up in Trombay, a suburb of Bombay.

In 1958, the government refashioned the AEC. Resolution No. 13/7/58-Adm called for the establishment of an AEC with ‘full executive and financial powers, modeled, more or less, on the lines of the Railway Board’ (DAE 1958, 10–11). The new AEC replaced the old one that had been set up within the Department of Scientific Research in 1948. Within the new AEC, the Secretary of the DAE was to ‘be the ex-officio Chairman of the Commission’.[11] The AEC was now responsible for formulating the policies of the DAE ‘for the consideration and approval of the Prime Minister’ and ‘for implementation of Government’s policy in all matters concerning atomic energy’. The chairman of the commission ‘shall be responsible under the Prime Minister for … advising Government on matters of atomic policy’. He would wield formidable powers since ‘all recommendations of the Commission on policy and allied matters shall be put up to the Prime Minister through the Chairman’, and since he ‘shall have the powers to overrule the other members of the Commission, except that the Member for Finance shall have the right to ask that any financial matter, in which he does not agree with the Chairman, be referred to the Prime Minister and the Finance Minister’.

The government did more than just provide money to the DAE. Various government agencies pitched in to promote nuclear power, and the nuclear establishment used these in many ways. For example, the DAE got the Films Division to make documentary films about various themes related to the nuclear programme, including BARC, uranium mining and Homi Bhabha (Sundaram, Krishnan, and Iyengar 1998, 129; FDI 2008). Such films constituted an excellent form of propaganda.[12] Not surprisingly, there were many who were brought up to think of atomic energy as the hope of the nation, and nuclear science as a hard subject to master. As literary critic and writer Amitava Kumar remembers from when he was growing up in the 1960s (2002, 3): ‘By the time I had learned to read, I had become aware that the smartest person in modern India was a man in Bombay called Homi Bhabha.’

By the early 1960s, the DAE was in a more or less comfortable place as an institution. This was further strengthened with Parliament adopting a revised Atomic Energy Act in 1962 that tightened secrecy and the Central government’s control over all nuclear activities. What was significant, as Itty Abraham notes, was that, for the most part, neither the act nor the debate that took place in Parliament when introducing the act, mentioned the by-then traditional focus on ‘peaceful uses’ (Abraham 1998, 114–20).

BOX 1.1

ORGANIZATIONS

The family of nuclear organizations in the country is headed by the Atomic Energy Commission. The AEC’s role is to formulate the policies and programmes and it is directly answerable only to the prime minister. The actual execution of these policies is carried out by the Department of Atomic Energy. The DAE is the equivalent of a government department but it turns to the AEC to clear all important programmes and projects, as well as its budget requests to the government. Once clearance has been obtained from the AEC, there is no need for separate approval from the ministry of finance. The space programme has borrowed this structure, with the Department of Space and the Space Commission playing the roles of the DAE and the AEC respectively (N.G. Raj 2000, 286–87).

The DAE has, in turn, set up a number of associated or subsidiary organizations. These include five research and development centres, five government-owned companies (‘public sector undertakings’), three industrial organizations and three service organizations (DAE 2010, Annex-I). The R&D centres that are most relevant to the activities covered in this book are the Bhabha Atomic Research Centre, the Indira Gandhi Centre for Atomic Research and the Atomic Mineral Directorate for Exploration and Research. The three most relevant government-owned companies are the Nuclear Power Corporation of India Limited, the Bharatiya Nabhikiya Vidyut Nigam and the Uranium Corporation of India Limited (UCIL). NPCIL is responsible for designing, constructing and operating the nuclear power plants within the first-stage nuclear power programme, that is, not breeder reactors.[13] Breeder reactors are BHAVINI’s responsibility, and the UCIL is in charge of the mining and milling of uranium. Industrial organizations include the Heavy Water Board (HWB)—in charge of the many plants that produce heavy water—and the Nuclear Fuel Complex (NFC), which manufactures fuel for the nuclear reactors.

In addition to these is the Atomic Energy Regulatory Board (AERB) which is supposed to oversee the safety of all nuclear installations that have not been demarcated as military. The latter category includes research reactors, reprocessing facilities and uranium enrichment plants. The AERB also regulates other facilities in the country that involve radiation in some way, for example, medical facilities and educational laboratories that use radiation sources. Following the government's introduction of the Nuclear Safety Regulatory Authority (NSRA) Bill in Parliament in September 2011, AERB is to be replaced by the Nuclear Safety Regulatory Authority.

LOOKING OUTSIDE

Despite much rhetoric about self-reliance and indigenous development, the AEC has sought and received ample help from other countries. Indeed, for the first quarter-century of its existence, until the nuclear weapon test of 1974,[14] the AEC kept on acquiring technologies related to the entire nuclear fuel chain from different countries. Practically all these were then proclaimed as domestically developed by the AEC.

The process started with Bhabha's embarking on a foreign visit in early 1948. Armed with a letter of reference from Nehru, Bhabha managed to get an offer of a tonne of uranium oxide from Canada to aid the atomic energy programme. France agreed to set up arrangements for the exchange and training of scientists and to share scientific information (Abraham 1998, 59). In 1952, Bhabha wrote a letter to the chairman of the US Atomic Energy Commission asking for 'all de-classified information on reactor theory, design and technology … detailed designs of such reactors that have been completely de-classified, together with all operational data' (Abraham 1998, 79). The letter also asked for 10 tonnes of heavy water, in return for which the Indian government offered thorium or uranium or beryl.

Bhabha also capitalized on the Cold War era desire of the United States and its allies to keep India out of the Soviet orbit and the US Atoms for Peace initiative. In November 1960, for example, while on a visit to Canada, he announced that the Soviet Union had agreed to design natural uranium and fast breeder power plants for India (Perkovich 1999, 37). The tactics soon paid off: Canada supplied the Rajasthan natural uranium reactors. Similarly, in 1961, faced with demands for safeguarding foreign-supplied nuclear reactors, Bhabha noted publicly that the Soviet Union would not insist on safeguards whereas Western nuclear powers would (*Statesman* 1961).[15]

India’s efforts to benefit from other countries were not restricted to technologies useful for nuclear generation of electricity; it also extended to weapons-usable information. For example, Vasudev Iya, a young chemist, was completing his doctoral degree at the University of Paris when Bhabha recruited him in 1955 (Sundaram, Krishnan, and Iyengar 1998, 54). He was sent to undergo training at the Saclay laboratories near Paris. Important among his task list was to learn about producing polonium, a chemical element used to trigger a nuclear explosion (Chengappa 2000, 85).

The practice of looking abroad for help continued after Bhabha. Almost immediately after assuming charge of the AEC, his successor, Vikram Sarabhai, sent a number of ‘senior scientists and engineers of the AEC’ to ‘the U.S., the USSR and France to acquaint themselves with the latest trends’. Later that year, in September 1966, Sarabhai himself ‘set off with a team … on a study tour to observe breeders and other forms of advanced reactor technology in the U.S.’ (A. Shah 2007, 167).

Research Reactors

As early as 1951, Sri Prakasa, the minister for natural resources and scientific research, had announced in Parliament that the construction of a small ‘atomic pile’ was an immediate object of the AEC (NYT 1951). India’s atomic establishment at this point did not have the ability to construct one by itself. In June 1954, to ward off criticism from people like Saha, Bhabha requested Sir John Cockcroft, an important figure in the British atomic programme and a colleague of Bhabha’s during his Cambridge days, to help India build a low-power research reactor. A few months later, Cockcroft offered detailed engineering drawings, technical data, and enriched uranium fuel rods for a ‘swimming pool reactor’ (Abraham 1997, 2140).[16] The AEC accepted the offer with alacrity and the first ‘indigenous’ reactor, Apsara, became critical in August 1956.[17]

Nehru’s speech at the inauguration of the reactor in January 1957 is a telling example of the propensity to claim local ownership of all nuclear artefacts: ‘We are not reluctant in the slightest degree to take advice and help from other countries … But it is to be remembered that this swimming pool reactor in front of you is the work, almost entirely, of our young Indian scientists and builders’ (Nehru 1958a, 507). Later the same year, while speaking to the Lok Sabha, Nehru even dropped the qualifier and bluntly asserted, ‘The putting up of the swimming pool reactor … was done entirely by Indian scientists and Indian engineers’ (Nehru 1958b, 517). Across the world, Cockcroft grumbled to his colleagues: ‘Did you see the press release from Delhi? … [It] seems rather ungracious in view of the advice and help we have given and are asked to give. Presumably, detailed plant designs and drawings do not constitute outside help!’ (Abraham 2006, 58).[18]

The second reactor to be set up was CIRUS—a 40-MW reactor that was moderated by heavy water, cooled by light water and fuelled by natural uranium (see Appendix 1 on nuclear reactor types).[19] It used the same design as the Canadian National Research Experimental (NRX) reactor. This deal involved another former Cambridge contemporary of Bhabha’s, W. Bennett Lewis, a senior official with Atomic Energy of Canada. Financial assistance for the construction of the reactor was provided by Canada as part of the Commonwealth’s Colombo Plan—a development assistance scheme ‘premised on the relation between misery and poverty and communism’ (Bothwell 1988, 352).

The construction of CIRUS also required the import of 21 tonnes of heavy water from the US. It was also an American firm, Vitro International, which was awarded the contract to prepare blueprints for the first reprocessing plant at Trombay. The plant was used to separate plutonium from the spent fuel rods irradiated at the CIRUS reactor; the plutonium was then used in India’s first nuclear weapon test of 1974. Between 1955 and 1974, 1104 Indian scientists were sent to various US facilities; 263 were trained at Canadian facilities prior to 1971 (Perkovich 1999, 30, 520).

Both Apsara and CIRUS were used for research; CIRUS also produced the plutonium that was used for the 1974 nuclear weapon test. But plans for this use to which CIRUS was put did not become public till that point. Even though some Canadian diplomats had realized that the possibility of producing plutonium for nuclear weapons existed, Bhabha adamantly refused to accept safeguards on the spent fuel from CIRUS; the Canadians agreed to this partly in anticipation of fierce competition in the nuclear reactor market (Bothwell 1988, 353; Fawcett 1994, 113).

Power Reactors

Neither Apsara nor CIRUS produced any electricity. For the AEC to show something for all the money they had been provided, they had to start generating electricity. And the AEC simply did not have the capability to design or construct a reactor on its own. In mid-1959, Bhabha turned to the people who had given India its first reactor, the United Kingdom Atomic Energy Authority (UKAEA), in particular Cockcroft, for a reactor to be fuelled by natural uranium (Parthasarathi 2007, 12).

The gas graphite reactor fuelled by natural uranium was the UK's niche. It used graphite as a moderator to slow down neutrons, and carbon dioxide to transport the heat produced. Graphite-moderated reactors had a respectable pedigree. The world's first pile constructed by Enrico Fermi and his collaborators in Chicago had consisted of uranium fuel rods emplaced in graphite blocks and cooled by air. Reactors used to produce plutonium for the atomic bombs of the US and the Soviet Union were of a similar design. The first reactor ever to be connected to the power grid was a gas graphite reactor at Calder Hall, UK, in August 1956 (Cowan 1990, 548).

Technically, the major advantage of the gas graphite design was that it did not require the enrichment of uranium, which led many countries to adopt it (Knief 1992, 296). The other reactor design that did not require enriched uranium was the CANDU pioneered by Canada, but this required heavy water. At the time when Bhabha approached the UKAEA, India had no capacity to produce heavy water, either.

The UKAEA assured Bhabha that it would provide a gas graphite reactor at a cost of around 600 million rupees (Parthasarathi 2007, 12–13). But when a global tender was put out, the UK bid Rs 950 million, followed closely by France at Rs 870 million. A surprised Bhabha made several trips to the UK to negotiate with the UKAEA, but in vain.

The unexpected winner was the American firm, General Electric Company (GE), which bid Rs 480 million for two 190-MW reactors, which were to be fuelled with enriched uranium supplied by the US. Though enriched uranium was not available within India, and the stated policy at that time was to construct only natural uranium-fuelled reactors, the pressure to generate electricity at the lowest possible cost trumped other considerations, and GE began constructing the Tarapur I and II reactors. The architecture and engineering part of the project was executed by

Bechtel Corporation, again from the US. When they came online in 1969, they generated nuclear electricity for the first time in the country.

In parallel, Bhabha also managed to work out a deal with the Atomic Energy Canada Limited (AECL) and the Montreal Engineering Company (MECO) to construct a 200-MW pressurized heavy water reactor, which is also fuelled with natural uranium, at Rawatbhata in Rajasthan. In April 1964, an agreement was signed between the Government of India and the Export Credit Insurance Corporation in Canada to cover the financing of materials and services from AECL and MECO (Graham and Stevens 1974, 23). Over a hundred Canadian consultants came to India for periods of one to two years while the reactors were being constructed.

The design adopted was a replica of the one at Douglas Point, Canada's first full-scale nuclear power plant, even though no operational feedback from this reference reactor was available to the designers at that time (Gopalakrishnan 2002, 375). This proved to be a premature choice and resulted in many of the problems faced in some of the DAE's PHWRs. The first of the reactors at the Rajasthan Atomic Power Station (RAPS I) was declared commercial in December 1973 and became the first of the many PHWRs that the DAE was to construct. Only a part of the construction of the second reactor at the same site, RAPS II, had been completed when the 1974 nuclear weapon test was conducted; in response, Canada pulled out of that project and the reactor was completed only in April 1981.

Heavy Water

Another crucial ingredient for the DAE's pressurized heavy water reactors —as the name indicates—is heavy water. Heavy water is water in which both hydrogen atoms have been replaced with deuterium, the isotope of hydrogen containing one proton and one neutron.[20] It is present naturally in water, but in only small amounts, one part or less in five thousand. For use in reactors, the heavy water must be concentrated to close to a hundred per cent. Its primary use is to slow down neutrons without absorbing them significantly. In many reactors, it is also used to carry away the heat produced during fission.

The first heavy water plant was set up in Nangal, next to the Bhakra Nangal Dam. The rationale for the location was that the process chosen for producing heavy water—the electrolysis process—would require large quantities of electricity, which could be drawn from the adjoining hydroelectric power station. Originally proposed by Bhabha in 1954, the plant commenced operations in 1962 (Parthasarathy 2007b). Overall engineering work of the Nangal plant was done by Vitro Corporation of the US, the contract for supplying electrolysers was awarded to Deonara of Italy, while the electric equipment was supplied by the English Electric Company of the UK. The contract for the associated hydrogen distillation plant was awarded to a company from Munich in Germany (Mirchandani and Namboodiri 1981, 61).

The next heavy water plant, set up in Baroda, used a different technology—the ammonia hydrogen exchange process—from a different country, France. For this plant, the DAE signed an agreement on 22 September 1969 with France, whereby the French government agreed to provide aid to cover the foreign exchange expenses for the purchase of equipment and know-how (Mirchandani and Namboodiri 1981, 63–64). The other plant that uses this process is the one at Tuticorin, which was constructed with Japanese and French assistance. Two other heavy water plants, in Kota, Rajasthan, and in Manuguru, Andhra Pradesh, have used the hydrogen sulphide water exchange process imported from Canada. Despite all these imports of technology related to heavy water from different countries, the DAE chooses to describe this history as developing 'heavy water technology indigenously starting from scratch' (A.L.N. Rao 2011, 177).

Fast Reactors

The next technology that the DAE sought internationally was a fast neutron reactor (see Appendix 1 on nuclear reactor types). In 1969, the DAE entered into a collaboration agreement with the French Atomic Energy Commission (CEA) and obtained the design of the Rapsodie test reactor and the steam generator design of the Phénix reactor (Rodriguez 2004, 350). This was to be the fast breeder test reactor (FBTR), India's first breeder reactor. The DAE subsequently entered into agreements during 1972 and 1973 with CEA 'for technical system consultancy and with four other French industries for the supply of manufacturing know-how' (CAG 1993).

As part of the agreement with the CEA, a team of about thirty engineers and scientists was trained at Cadarache, France. After they returned, they formed the nucleus of the Reactor Research Centre (RRC) that was set up in 1971 at Kalpakkam to lead the breeder effort (Rodriguez 2004, 350–52). This was renamed the Indira Gandhi Centre for Atomic Research in 1985.

In December 1968, while the initial efforts to set up the FBTR were going on, P.K. Iyengar, who was to head the AEC in the 1990s, toured the nuclear research facilities in Dubna, Soviet Union, and was very impressed by a small pulsed fast reactor that uses plutonium as fuel (Chengappa 2000, 121). Returning to India, Iyengar led the team that constructed a similar reactor called Purnima, which then provided 'data vital to the design' of the bomb that was exploded in May 1974 (Perkovich 1999, 149).

THE NUCLEAR JANUS

Purnima is a good example of the dual characteristic of nuclear technology. At the time that Purnima was approved, the official position of the Indian government was that it only supported the peaceful uses of nuclear technology. Earlier in 1964, a public debate between Bhabha and Prime Minister Lal Bahadur Shastri resulted in the latter eventually agreeing to allow work towards building peaceful nuclear explosives (PNEs) 'for the development of our nation' (Perkovich 1999, 65–83).[21] Following Bhabha's death, Vikram Sarabhai, who was far more categorically opposed to nuclear weapons than Bhabha, became head of the AEC. But there were limits to his ability to change course. 'Sarabhai could not keep scientists from doing their work. He couldn't look over our shoulders,' Raja Ramanna, one of the leaders of the 1974 test, acknowledged in a private interview (Perkovich 1999, 123).

And yet, it was Sarabhai who, in 1968, approved the construction of the Purnima reactor. He did so not to further nuclear weapons design but to accelerate plutonium-based fast breeder technology for electricity generation (Hymans 2006, 183). What was learnt from the Purnima reactor was physical details like, how long a neutron could survive before it was absorbed by plutonium, and how effective different materials would be in reflecting neutrons. Such details were useful both in building fast neutron reactors and in designing a nuclear weapon with a plutonium core. Sarabhai might well have been interested in the former, but those who proposed the reactor and many of those who worked in the Purnima team were probably more interested in the latter. As Iyengar was to put it several years later, by using the data from Purnima, 'physicists could … calculate the time behaviour of the core of a bomb on isotropic compression. What the critical parameters would be, how to achieve optimum explosive power, and its dependence on the first self-sustaining neutron trigger, were all investigated' (Iyengar 1994). Many on the Purnima team went on to participate in the Pokhran tests (Sundaram, Krishnan, and Iyengar 1998, 26).

Purnima is not the only example; reprocessing offers an even more striking illustration of the dual-use capabilities of technologies related to nuclear power. Almost from the very beginning, the DAE was intent upon acquiring the capability to chemically process ('reprocess') irradiated nuclear fuel to extract plutonium. The DAE's public rationale for pursuing the separation of plutonium was its use in breeder reactors (Bhabha 1958, 406). But, in reality, the plutonium could just as well be used in nuclear weapons. The nature of the DAE's priorities for plutonium may be inferred from the fact that the first nuclear explosion conducted by the DAE was in 1974, whereas the first breeder reactor became critical only in 1985.

For many around the world, the myth that the DAE was intent only on peaceful uses of technology was shattered in 1974 in Rajasthan's Jaisalmer district, near the sleepy town of Pokhran. Though the town's fame in contemporary times started with this nuclear weapon test, the existence of the town dates back many centuries. It was a halting place for caravans that travelled an ancient trade route running towards the Arabian Sea. Nearby is a fourteenth-century red sandstone fortress that has now been converted into a hotel (Pokaran 2005).

In the late 1960s, construction of a firing range started near the town (Bhattacharya 1982). First, two villages, Malka and Kala, were evacuated. Then, in 1971, four more villages—Naotala, Etah, Taorki and Sudhia—followed (Bhattacharya 1982, 12). From then on, residents of the nearby areas had to get used to the screeching of warplanes and the bursting of artillery shells. On 18 May 1974, around eight in the morning, they heard a different sound—a loud bang, followed by the earth moving, windows breaking and walls shaking. Those who did not know the source of the sound found out—along with millions of other Indians—through a special announcement on All India Radio that 'India successfully conducted an underground nuclear explosion for peaceful purposes at a carefully chosen site in western India' (Chengappa 2000, 201).

The test involved a 'device' that weighed about 1500 kg, with 5–7 kg of plutonium, and placed in a shaft that was 107 m deep and 7 m wide (*Economic Times* 1998). The yield of the test—the energy released when a nuclear weapon explodes—officially was 12 kilotonnes (Chidambaram and Ramanna 1975, 429). For historical reasons, the yield is usually measured in kilotonnes or megatonnes of TNT equivalent, that is, as much energy as thousands or millions of tonnes of chemical high explosive. One tonne of TNT releases 4.2 billion joules of energy upon detonation. To get a sense of scale, a 100-watt incandescent bulb consumes 360,000 joules of electrical energy every hour.

There is reason to believe that the yield of the 1974 explosion was lower than this stated figure. In private interviews, former heads of the AEC were more circumspect and used figures like 8–12 kilotonnes; on one occasion, P.K. Iyengar even said to scholar George Perkovich that the yield was between 8 and 10 kilotonnes, and the device was designed to only produce 10 kilotonnes (Perkovich 1999, 182). US technical analysts estimate the yield at around 4 to 6 kilotonnes (Wallace 1998, 388–89).

But publicly, DAE officials always maintained that the yield of the 1974 test was 12 kilotonnes (Chidambaram and Ramanna 1975; Chidambaram and Ganguly 1996). That is, till the 1998 nuclear tests. The signals from both the 1974 and 1998 tests were detected by seismometers—instruments used to measure earthquakes and tremors—around the world. In both cases, seismologists around the world estimated the yield at values lower than the DAE's claims. In 1998, this difference of opinion became controversial. To answer the criticisms by international seismologists, the DAE chose to ignore its own official estimate of 12 kilotonnes and rely on an unpublished estimate of 13 kilotonnes calculated by the 'Procurement Executive, Ministry of Defence, United Kingdom' using 'surface wave data at Quetta' in Pakistan (Sikka, Roy, and Nair 1998, 491). The variation might seem minor but leads to a difference of 5 kilotonnes for the 1998 tests.

Officially, what happened in May 1974 was a peaceful nuclear explosion (PNE). Sometimes, it is termed a peaceful nuclear experiment, so that even its explosive character is camouflaged. The irony is that most official discussions of that event start with a discussion of the strategic environment of India, in particular China’s first nuclear test of 1964 and Pakistan’s nuclear weapons ambitions, clearly suggesting that the PNE was to be seen as a response to these changes. Its intentions were thus explicitly militaristic in origin.

That said, the term PNE was prevalent in the 1960s, and it was easy for the DAE to latch on to it as a cover for their interest in nuclear weapons. It was coined during the height of the Cold War, and talking about PNEs was a way for weapons laboratories in the US and the Soviet Union to gloss over their efforts to develop weapons that could destroy millions of people, and portray their work as something that had constructive purposes. ‘To a man with a hammer,’ wrote Mark Twain, ‘everything looks like a nail.’ Similarly, nuclear weapons designers went around trying to find applications—such as mining and creating large cavities—which might call for large quantities of explosive power, as possible arenas for using PNEs.

In late 1957, the US had established a formal programme to conduct PNEs. It envisioned using them for massive excavation projects, such as digging canals and harbours, and releasing underground oil and gas. At the second UN Conference on Peaceful Nuclear Explosives, the US extolled these benefits to an international audience, including leaders of the AEC (Perkovich 1999, 35).

The DAE, too, tried to put forth arguments that PNEs could be used to achieve such benefits. AEC Chairman Sarabhai, who seems to have been opposed to the bomb, apparently came around to accepting the idea of a PNE. He even invented a term for it: nuclear explosives engineering (NEE). Sarabhai commissioned N. Seshagiri of the Tata Institute of Fundamental Research to do a cost–benefit analysis of various applications of PNE (Sundaram, Krishnan, and Iyengar 1998, 179). There could not have been a better man for the job. Seshagiri went to town on the idea.

Not only did Seshagiri find that NEE was economical, he even went so far as to add it to Bhabha’s three-phase programme. As the second and third phases went under way, Seshagiri (1975) argued, the plutonium-239 and the uranium-233 developed for reactors could also ‘be utilized to develop a full-fledged NEE capability of plutonium fission explosives, uranium fission explosives, uranium fission-triggered fusion explosives, plutonium fission-triggered fusion explosives, and finally laser-triggered fusion explosives'. Though hard, this path, Seshagiri felt, would 'be immensely rewarding' (25).

But even before these results came out publicly in 1971, Sarabhai announced at a news conference that he favoured underground explosions 'for the economic benefit of the country', emphasizing that India was not working on a nuclear weapons programme. The potential benefits he listed included 'extracting low grade copper and nickel ores and exploitation of oil' (NYT 1970a). Not that any copper or nickel or oil came from Pokhran or anywhere else in India by exploding nuclear devices.

All this talk of PNEs was, and continues to be, disingenuous. There is inherently no difference between a PNE and a nuclear weapon. The one putative difference is that a PNE need not be limited by weight, unlike nuclear weapons, which have to be delivered by a plane or a missile. But a PNE can, for sure, be a stepping stone to designing a nuclear weapon, and a light one at that, if so desired.

Given this inherently close connection, one beneficial fallout of the 1974 test was that it put a stop to the charade of peaceful explosions. It was, as R. Chidambaram, a leader of the team that had designed the weapon tested in 1974 and subsequent chairman of the AEC, put it, 'the PNE that ended all other PNEs' (Bagla and Menon 1994, 79). Good riddance, one might add.

INTERNATIONAL RESPONSE

The 1974 test also ended the period of extensive foreign support to the nuclear programme, despite the government's diplomatic offensive to establish that the 18 May explosion was indeed peaceful. The international community—led by Canada and the US, who were incensed by India's use of plutonium from CIRUS that had been given to India for purely peaceful purposes—cut off most material transfers relating to the nuclear programme. Even countries like Japan which had no nuclear dealings with India cut off foreign aid (Power 1979, 576). One exception was the Soviet Union, which 'merely reported India's action, repeating India's claim that it was for peaceful purposes' (Mehrotra 1990, 21).

The US and other countries agreed on a code of conduct aimed at preventing exports made for commercial and peaceful purposes from being used to make nuclear weapons. This eventually became the Nuclear Suppliers Group (NSG) Guidelines, which list specific nuclear materials, equipment and technologies that are subject to export controls. Three decades later, the US was to lead the effort to exempt India from precisely these guidelines through what became known as the US–India deal.

There are two parts to the NSG Guidelines. Part I was created in response to India's 1974 test, and lists materials and technology designed specifically for nuclear use, including fissile materials, nuclear reactors, and reprocessing and enrichment equipment. A subsequent part was adopted in 1992, after discovering how close Iraq had come to making nuclear weapons material by employing dual-use imports in a covert programme. Part II lists dual-use goods, such as, machine tools and lasers, which are non-nuclear items but which can also be used to develop weapons. Those countries that are parties to the Nuclear Non-Proliferation Treaty (NPT) and agree to abide by the NSG Guidelines may be admitted into the Nuclear Suppliers Group.

Many countries put domestic legislation into place as well. Canada was the first to do so in 1976. As supplier of the CIRUS reactor—the source of the plutonium for the 1974 nuclear test—Canada felt partly responsible for the event. Within four days of the tests, Secretary of State for External Affairs Mitchell Sharp stated that shipments of nuclear equipment and material to and technical cooperation with India had been suspended (Noble 2006, 80). In December 1974, a new policy required a binding assurance that Canadian nuclear material, equipment and technology would not be used for a nuclear explosive device, explicitly prohibiting 'peaceful nuclear explosions', and instating other safeguarding agreements. And finally, in December 1976, the Canadian cabinet announced that nuclear trade would be restricted to those countries that had signed the Nuclear Non-Proliferation Treaty. In 1978, the US Congress passed the Nuclear Non-Proliferation Act (NNPA) that required every country—other than the five nuclear weapon states that were signatories to the NPT—to accept International Atomic Energy Agency (IAEA) safeguards on all its nuclear facilities ('full scope safeguards') before the US would engage in any nuclear cooperation with it.

The Indian government's refusal to give up its nuclear weapons and sign the NPT meant that no NSG state, including the US, would sell nuclear technology to it—at least, until 2008. In reality, though, even between 1974 and 1998, this embargo has not been strictly followed and commercial or other institutional interests have sometimes overridden non-proliferation considerations. One example is the case of the Tarapur I and II reactors that were supplied by the US with an agreement that guaranteed fuel supplies for thirty years following the inking of the agreement in 1963. With the 1978 NNPA being passed, however, the US could no longer supply fuel but, after long-drawn negotiations under the Carter and Reagan administrations, it facilitated India's purchase of enriched uranium fuel (which the DAE did not have the capacity to manufacture in adequate quantities) from other countries. France (1983–93), China (1995–98) and Russia were among the countries which sold enriched uranium fuel to India for those reactors. Russia did so despite being a member of the NSG by using an exception clause—somewhat disingenuously—that allows for the sale of material or equipment in cases where they are deemed indispensable for the safe operation of the facility (Fedchenko 2001, 24). Likewise, Russia also supplied the reactors being constructed in Koodankulam in southern Tamil Nadu by claiming that the agreement governing that deal was signed in the 1980s by the then Soviet Union before it joined the NSG.

Various other nuclear facilities too procured components from abroad, though only to a small extent, and foreign consultants continued to be hired for Indian nuclear projects.[22] DAE personnel continued to have access to nuclear literature and participated in international conferences where technical details were freely discussed.

The continued contact between the community of nuclear engineers and scientists also proved helpful to the DAE. As P.K. Iyengar was to say explicitly in an interview to a Canadian newspaper, 'The scientists have always been friendly [and] are not the problem. It's [the] Foreign Affairs people' (Stackhouse 1998). The main 'problem' that Iyengar was referring to was the inability to import nuclear reactor components. Iyengar, who had received his early training at the Chalk River facility in Canada, also admitted that he and his colleagues frequently visited Canada in the 1980s and early 1990s, and 'exchanged notes' with Canadian scientists.

Even though the idea that the DAE was totally cut off from the rest of the nuclear energy sphere is not tenable, it provided a convenient excuse for failures and the possibility of taking sole credit for any achievements, however minor. The nuclear establishment also never missed an opportunity to criticize the decision of other countries to refuse to sell reactor and other technologies. Former AEC chairman M.R. Srinivasan, for example, described these as ‘unreasonable regimes of technology denials’, and praised the DAE’s ‘wide range of technological capabilities’ that helped the country ‘stand up’ to them (M.R. Srinivasan 1997, 143). Even stronger language was adopted on occasion, and there were references to ‘nuclear apartheid’ against India.[23]

The Effects

Despite the brave front put up by the DAE and its frequent claims about self-reliance, it is obvious that its plans for nuclear power did receive a serious setback. The first reactors to be affected by the fallout of the 1974 test were the ones that were already under construction: RAPS II and the FBTR. Even with help from the Canadians, the first of the Rajasthan reactors, RAPS I, had been delayed by over four years.[24] The fate of RAPS II was worse and it took eight years more than the expected time.[25] The FBTR, which was initially supposed to be ready by 1976 (CAG 1993), finally started operating only in October 1985. Its steam generator began operating in 1993 (Hibbs 1997b, 10).

Delays were also experienced in the PHWRs that were next in line: the Madras and the Narora atomic power stations. As per the DAE’s plans, MAPS I and II and NAPS I and II were to come online in successive years from 1975 through 1978 (AEC 1970, 16). The MAPS I unit eventually began commercial operation in January 1984 and MAPS II began in March 1986. The Narora units were to begin only in 1991 and 1992.

Unreasonable expectations of the domestic industry, which was unable to manufacture quickly enough some of the specialized equipment required for setting up nuclear reactors, also contributed to the delay. As the Estimates Committee of the Parliament (Sixth Lok Sabha, 1977–78) put it, ‘the shortfall in the plan’ was ‘mainly attributed to delay in the supply of equipment by indigenous manufacturers [and] non-availability of essential raw materials like steel, coal, cement, etc.’ (Mirchandani and Namboodiri 1981, 34).

The problem, however, was not that the industry lacked the technological base and knowledge needed to carry out the fabrication, but that the few orders that it received from the DAE did not make it economical for companies to do so. Many were therefore reluctant, and those that did undertake manufacturing orders from the DAE did so at great expense. This was reflected in the much higher costs for these pieces of equipment. For example, the turbo-generator for RAPS I was imported from Canada for Rs 64 million while the same component for RAPS II from a domestic manufacturer cost Rs 130.4 million (Mirchandani and Namboodiri 1981, 35).

The delays in reactor commencements were matched by similar delays in other components of the fuel chain. Among them was the reprocessing of spent fuel to extract plutonium. Though the first reprocessing plant in Trombay that was the source of plutonium for the first nuclear weapon test had been completed in 1965, the first commercial-scale reprocessing plant (PREFRE) at Tarapur to deal with the spent fuel from power reactors was effectively delayed by over a decade.[26]

While spent fuel could simply be stored in water-filled pools while waiting for reprocessing plants to come online, the case was not so simple with heavy water, another essential ingredient for reactor operations. Some reactors could not be commissioned because of the DAE's inability to produce adequate amounts of heavy water (see chapter 5).

All these delays were in activities connected with producing nuclear electricity. In order to provide a means of producing plutonium for weapons without, if necessary, involving CIRUS, the DAE built a reactor called Dhruva. Dhruva is modelled after CIRUS, but uses heavy water as both coolant and moderator so as to further reduce neutron losses. This increases the rate of plutonium production. It was commissioned in 1985 but had severe operating problems in the first few years and reportedly began normal operations only in 1988 (Chellaney 1987, 9; Hibbs 1992a, 8).

For many DAE scientists such delays must have been hard to swallow. To the extent possible, they tried to put the best face on the situation and the top leaders tried to motivate the personnel in the DAE's facilities. Illustrative of this are the comments of the BARC director in 2001: 'We are really comfortable when we work under sanctions. Our scientists and engineers enjoy working under sanctions because it acts as a catalyst for all of us, from the lowest level to the topmost level, to give our best' (Bhattacharjee 2001).

On the other hand, there seem to be many in the DAE who feel that the 1974 test extracted a heavy price from the nuclear power programme. An example of this is the statement by N. Srinivasan (1998), a former member of the AEC and the first director of the RRC in Kalpakkam, soon after the May 1998 nuclear tests: 'I have a sad feeling that the first nail was driven in the coffin of the nuclear power programme in May '74 and the last nails have now been hammered in, in May '98' (10).

Lessons Not Learnt

If there was one aspect of the DAE's functioning that the nuclear export control regime could not change, it was its penchant for making unrealizable projections. In 1984, a decade after the 1974 nuclear weapon test, the DAE drew up a new atomic energy profile that envisioned setting up 10,000 MW of nuclear power by the year 2000 (CAG 1999). Raja Ramanna, as chairman of the AEC, presided over the exercise. The profile

> proposed to start work on 12 additional 235 MWe units during the VII five year plan of which 9 will be commissioned by the end of the VII five year plan and the nuclear power generating capacity would reach 5,000 MWe by 1996.[27] The design of 500 MWe PHWR unit is being finalised and construction work on the first unit is also proposed to be started during the VII five year plan period and the unit is expected to come on stream by 1996. Additional 9 units of 500 MWe each are proposed to be completed during 1996–2000 which would take the nuclear power generation capacity to 10,000 MWe. (Ramanna 1985)

Even without the wisdom of today's hindsight, it should be obvious to anyone who knew the history of construction of the operating reactors—TAPS I and II, RAPS I and II, and MAPS I—that the projected growth in nuclear capacity was highly improbable if not impossible. But such comprehension was not to be found within the DAE's leadership. In July 1988, four years after the profile was publicized, the DAE appointed a committee for updating the profile and making recommendations about the schedule to be adopted for the setting up of plants and laying out of input requirements to meet with the scheduled construction of plants (CAG 1999, 14). After reviewing the implementation of the profile to date, which was pretty much invisible to the outside world, the ‘committee came to the conclusion in November 1989 that the overall target of establishing an installed capacity of 10,000 MW by 2000 AD continued to be feasible’ (CAG 1999, 14).

What actually materialized from the profile was even more shocking than expected. As the Comptroller and Auditor General noted in its 1999 report: ‘Against the targeted additional power generation of 940 MW by 1995–96, gradually increasing to 7880 MW by 2001 AD, the actual additional generation of power under the profile as of March 1998 was nil in spite of having incurred an expenditure of Rs 5291.48 crore’ (CAG 1999, 20). Nil, as in zero. In the words of Polonius from *Hamlet*, ‘… ’tis true ’tis pity; / And pity ’tis ’tis true.’

There is some irony in looking back at this projection from the vantage point of 2012. The foremost amongst the reasons given by the AEC chairman for settling on the (round) number of 10,000 MW was that ‘the life-time requirement of uranium for the PHWR units having gross capacity of 10,000 MWe can be met by the resources already identified’ (Ramanna 1985). In late 2007, with the total nuclear generating capacity in the country at 4120 MW, less than half of the 10,000 MW projected for 2000, the head of Nuclear Power Corporation of India Limited (NPCIL) announced that uranium fuel shortages had led to five of the country’s seventeen nuclear power plants being shut down and the rest being run, on average, at half power. Not only had the DAE failed to build nuclear reactors at the pace envisioned, but it had also been unable to mine uranium at a rate sufficient to fuel even those that had already been constructed (see chapter 3). Clearly, between projections and project management, there has been a yawning gap.

1998 AND BEYOND

A change of regime is often dangerous. After 1947, the Congress party had ruled the country for the most part. This partly explained why there had been continuity in both nuclear energy and weapons policies. The continuity in the latter realm changed drastically in 1998 when the Bharatiya Janata Party (BJP) came to power.[28] Weeks after coming to power, the new government conducted five nuclear tests vitiating peace and security in South Asia (Bidwai and Vanaik 1999; Ramana and Mian 2003).

This was a godsend for the DAE which had been under some attack because it had failed to deliver on its projections of thousands of megawatts. Ever since 1974, it had lobbied, unsuccessfully thus far, to conduct further nuclear tests and expand the country's nuclear arsenal (Ramana 2003). With the tests, it could fully establish its credentials as the organization that built the 'ultimate weapon' for the country.

Delivering bangs did produce the bucks. Over the decades, practically all governments have favoured nuclear energy and the DAE's budgets have always been high. The only period when the DAE did not get all that it asked for and therefore considered 'a period of total dryness and stagnation' were the early 1990s, a period marked by cutbacks on government spending as part of economic liberalization (Iype 2000).[29]

But this trend was reversed with the 1998 nuclear weapons tests and the DAE's budget increased from Rs 19.96 billion in 1997–98 to Rs 37.38 billion in 2003–04. The trend persisted even after the BJP lost power and the Congress won the 2004 elections. Budget allocations increased continuously, with the sole exception of the 2007–08 Budget, and reached Rs 81.57 billion in 2010–11 according to the annual expenditure budgets of the Government of India. Its proposed budget for 2011–12, the latest at the time of writing, was Rs 93.52 billion; this figure is the net expenditure budget, after accounting for all the revenues the DAE expected to receive. In comparison, the proposed 2011–12 Budget of the ministry of new and renewable energy was Rs 12.12 billion, offering testimony to the government's priorities. To put that in perspective, according to the Central Electricity Authority, as of 29 February 2012, the total generating capacity of renewable energy projects was 22,233 MW whereas the installed capacity of nuclear power was 4780 MW.[30]

With so much money being poured in, the DAE could not continue to bask in the explosive limelight for too long. In any case, just focusing on the production of nuclear weapons would not help the DAE. As discussed in the introduction, the DAE's institutional power came, and comes, from a unique combination of abilities: it was, and is, the only entity that can *claim* to address *both* the goals that the State desires in order to establish its legitimacy, namely, military security and development. The 1998 nuclear tests were supposed to address the first goal, and indeed they did so in the eyes of much of the political elite.[31] Therefore it was time—the DAE seemed to have decided—to move back to harping on future nuclear power potential.

It now had a new target with a nice rhythmic ring: 20,000 MW by 2020 (A. Joseph 1999). But there was a problem. Not even in its unbounded optimism could it envision doing this on its own. Therefore, in September 1998, a few months after the nuclear tests, R. Chidambaram, the AEC chairman, talked at the IAEA of 'procurement of LWRs [light water reactors] from friendly countries' (PTI 1998). The only friendly country at that point was Russia.

The story of why and how Russia became a 'friendly country' began formally in 1988 (see chapter 2). That year, India and the then Soviet Union signed an agreement to build reactors in Koodankulam. According to the agreement, the Soviet Union was to provide concessional state-to-state credit for the reactor, priced then at Rs 47 billion. This was barely two years after the Chernobyl disaster, and the Soviet nuclear industry was desperate to improve its image. But with the collapse of the Soviet Union, project plans were shelved.

The project lay dormant for a time because of uncertainties in Russia, but with the improvement of the Russian economy, it was officially revived in June 1998. By then, the project cost had risen to over Rs 130 billion, for which Moscow again agreed to extend state credit. Once more, a significant factor in the resuscitation of the Koodankulam plan was the sorry state of the Russian nuclear establishment, which was suffering from the migration of skilled personnel to the West, as well as a dwindling number of orders.[32] For its part, the DAE was keen on finding a country to break ranks and flout the international understanding that nuclear commerce was not to be conducted with India.

Russia was willing to go further. In 2000, during his visit to India, President Vladimir Putin made it a point to go to BARC and announce that Russian cooperation would not be limited to the Koodankulam project. The two countries announced a protocol on nuclear cooperation. However, this was not to happen for a while. Russia reportedly 'informed India in mid-

2002 that New Delhi had to find a way of getting the Americans on board. A wink and nod from the US would be necessary' (Raja Mohan 2004, 131). That was not to come till the US–India nuclear deal.

Nevertheless, the DAE assumed that Russia or some other friendly country would deliver 8000 MW of LWRs. The DAE could then use the plutonium obtained by reprocessing spent fuel from these LWRs and employ it to build breeder reactors. Based on this idea, in 2004, DAE analysts projected that by 2052, the nuclear establishment would construct nuclear reactors with a total capacity of 275,000 MW, or 275 GW (Grover and Chandra 2004).[33] This is an utterly fantastic figure if one looks at what it would entail.

If the build-up were to be carried out at a steady pace, then, each year, the DAE would have to install over 5400 MW of nuclear capacity for the next fifty years. That was *twice the amount of the existing capacity* at the point when the projections were being made. If the growth were to be slower in the beginning, then the installation rate would have to be even higher in the later years.

One can also compare this with worldwide experience. Between 1981 and 1990—the decade that saw the most rapid worldwide growth of nuclear power—about 20 GW of generating capacity was added globally every year (Keystone 2007, 25). Within a single country, the highest construction rate has been in France, which added about 39 GW during the same decade, or 3.9 GW/y (IAEA 2012). Thus, the average rate of reactor construction according to the DAE would be more than the French average, more than a quarter of the global average, and would be maintained at that rate for nearly five decades.

The US–India nuclear deal (see Appendix 2) prompted yet another round of extravagant claims about the importance of nuclear power for the nation's development. Cabinet Minister for Power Sushilkumar Shinde said in an official statement, 'the U.S. will help us add 40,000 MW of nuclear power by the year 2020,' adding, 'this will go a long way in addressing our energy deficit and will give an impetus to the country's economic growth and sustainable development' (ToI 2008). The US–India Business Council, an organization that must have been salivating at the prospect of some of its members partaking of a significant fraction of reactor sales and related commerce, estimated the cost that would be incurred at US$ 100 billion or about Rs 5 trillion (Sasi 2008). There were no details about what assumptions go into this figure and it is entirely possible that this was exaggerated in order to convince US legislators to approve various changes in US law in order to allow for nuclear trade with India. Nevertheless, this figure is over fifty times the DAE's budget for 2011–12 of about Rs 93 billion. If even a fraction of the claims of those pushing the nuclear deal were to come true, the costs would be astronomical.

True to its style, the DAE looked even further and higher. DAE Secretary Anil Kakodkar now predicted that nuclear power would constitute not 20 per cent but 35 per cent of electricity generation capacity in 2050. This was in effect echoed by Prime Minister Manmohan Singh who announced that India would have 470 GW of nuclear power by mid-century, more than a hundred times the nuclear capacity that existed at the time of the announcement.

This chapter has tried to offer a retrospective perspective on the nuclear establishment's quest to generate large amounts of nuclear electricity in India. Despite generous government funding for decades, this has not happened. However, the immense political power wielded by the DAE and the desire on the part of decision-makers to transform India into a nuclear power—in all its meanings—implies that prospects remain high for continued high-level political support for the DAE's grandiose aims. But, as in the past, political support alone cannot result in a rapid expansion of nuclear power, certainly not on the scale that the DAE has projected and political leaders have echoed. Nuclear power around the world has been marked by failures, though seldom on the scale of the DAE's failures. The continued expectation that nuclear power will, some day, energize the country in a substantial fashion is well captured by what Fitzgerald says about the eponymous hero of *The Great Gatsby*:

> Gatsby believed in the green light, the orgiastic future that year by year recedes before us. It eluded us then, but that's no matter—tomorrow we will run faster, stretch out our arms farther … And one fine morning—So we beat on, boats against the current, borne back ceaselessly into the past.

2

Power Reactors

> *Let us make recommendations to ensure that NASA officials deal in a world of reality in understanding technological weaknesses and imperfections well enough to be actively trying to eliminate them. They must live in reality in comparing the costs and utility of the Shuttle to other methods of entering space. And they must be realistic in making contracts, in estimating costs, and the difficulty of the projects. Only realistic flight schedules should be proposed, schedules that have a reasonable chance of being met. If in this way the government would not support them, then so be it. NASA owes it to the citizens from whom it asks support to be frank, honest, and informative, so that these citizens can make the wisest decisions for the use of their limited resources. For a successful technology, reality must take precedence over public relations, for nature cannot be fooled.*
>
> —Richard Feynman in his analysis of the 1985 Challenger Space Shuttle Accident

‘The atomic energy organization,’ says M.R. Srinivasan, head of the DAE in the 1980s, ‘set for itself the task of harnessing the power of the atom (or, more strictly, that of the nucleus) to produce abundant, inexpensive energy to transform India into a modern society’ (M.R. Srinivasan 2002, 37). An important part of this task was constructing power reactors around the country. As of September 2012, there are twenty operating reactors on six sites with plans to build reactors in several more.[1] Most operating reactors are pressurized heavy water reactors but there are two light water reactors with plans for more. There is one small pilot-scale fast breeder reactor, but future projections imagine building hundreds of breeder reactors—literally.

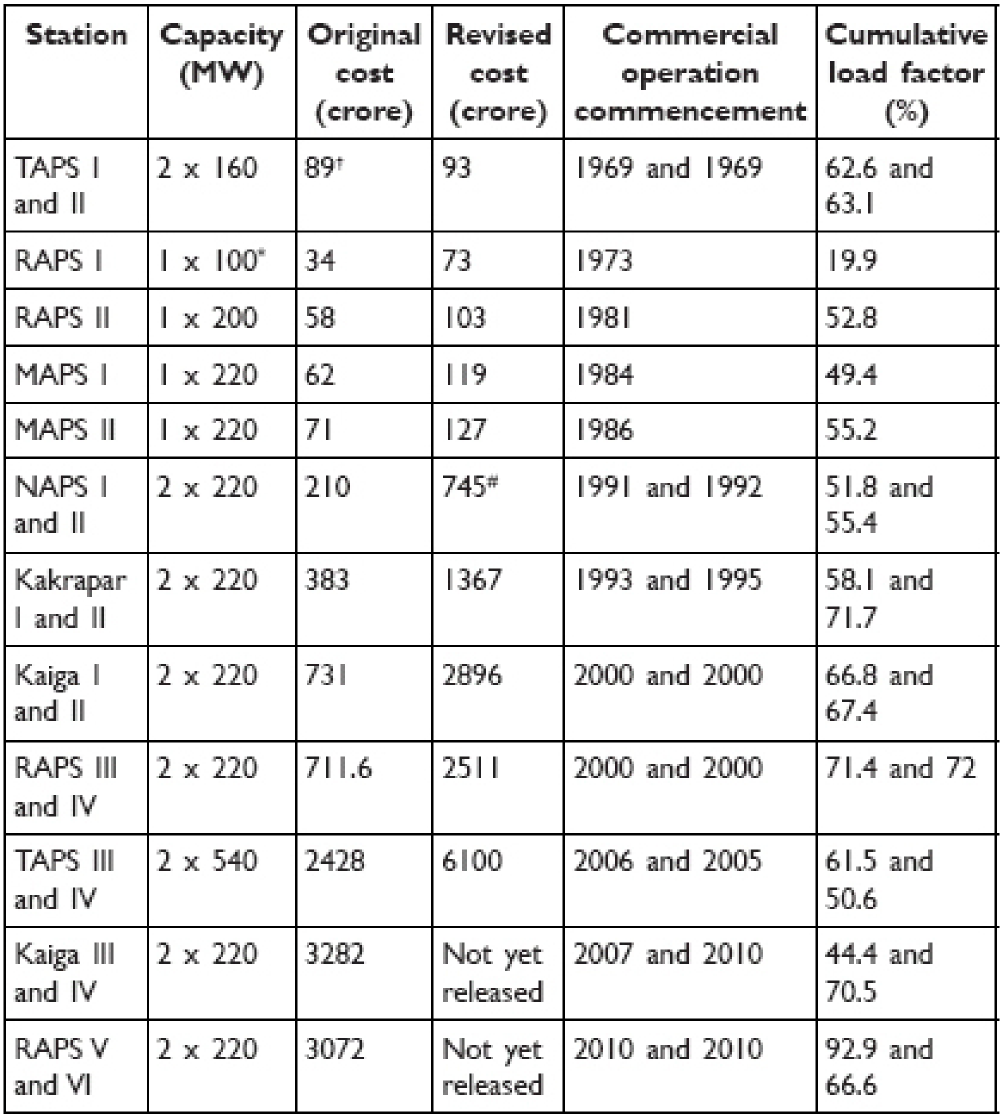
The question of whether this expansion makes sense can be addressed in part by looking at what the construction of existing reactors has entailed. This chapter examines the power reactors constructed so far, and it is organized by reactor site, in a roughly chronological fashion. Practically each case demonstrates that the reactors took longer to build, cost more than projected, and have performed worse than had been envisaged when plans were made. Almost always, there were problems that had not been envisioned when the site was selected, leading to delays in construction and reduced efficiency in operations.

A number of problems that cropped up in the PHWR design used in many of the reactors constructed by the DAE resulted from the adoption of a design that had not been tested anywhere in the world. That, unfortunately, is likely to happen again. The DAE plans to construct at least four more breeder reactors by 2020 (*Hindu* 2007b). Their designs will be a modified version of the design of the prototype fast breeder reactor under construction in Kalpakkam.[2] Since that reactor is unlikely to start operating before 2013, the DAE will at best have a couple of years of experience with the reactor before it begins construction of new reactors. The LWR designs proposed for Jaitapur, Kovvada and Mithi Virdi have all never been operated anywhere.

The performance of the DAE's reactors has been spotty at best. Each year, the International Atomic Energy Agency collects performance information on all power reactors in the world. This is fed into what is called the Power Reactor Information System (PRIS) database, and various performance indicators are calculated. The most important among these is what is called the load or capacity factor, which is the ratio of the actual amount of energy produced to the amount that could have been produced had the reactor been operating continuously (that is, 24 hours a day, 365 days a year) at design power.

For a long time, the DAE's reactors were among the poorest performers in the world. The April 1995 issue of *Nuclear Engineering International* (NEI), a standard trade journal, found that the average lifetime load factor for Indian reactors was 36.08 per cent, the lowest among the eighteen countries with four or more nuclear reactors; only Brazil, with just one reactor, fared worse (Howles 1995, 27). Four years later, this position was unchanged (NEI 1999, 25). It was only after the year 2000 that the performance of the DAE's reactors improved. This suggests that the NPCIL may have overcome its teething problems. But it also reflects the dramatic increases in funding for the DAE (see chapter 1). Further, at the level of individual reactors, performance has remained erratic.[3] The cumulative or lifetime load factors of the DAE's reactors as of the end of 2011 are listed in Table 2.1. Despite the improvements, the performance figures are far from satisfactory and offer one more reason for not trusting the DAE’s studies of the economic competitiveness of nuclear power, which are based on assuming load factors of 80 per cent, much higher than any DAE reactor has managed to maintain over an extended period of time. Note also that there are striking variations in performance among different units at the same site, suggesting that even with near identical designs, there is much that is unpredictable about nuclear reactor operations.

TABLE 2.1: CAPITAL COSTS OF OPERATING REACTORS



Station	Capacity (MW)	Original cost (crore)	Revised cost (crore)	Commercial operation commencement	Cumulative load factor (%)
TAPS I and II	2 x 160	89[†]	93	1969 and 1969	62.6 and 63.1
RAPS I	1 x 100[*]	34	73	1973	19.9
RAPS II	1 x 200	58	103	1981	52.8
MAPS I	1 x 220	62	119	1984	49.4
MAPS II	1 x 220	71	127	1986	55.2
NAPS I and II	2 x 220	210	745[#]	1991 and 1992	51.8 and 55.4
Kakrapar I and II	2 x 220	383	1367	1993 and 1995	58.1 and 71.7
Kaiga I and II	2 x 220	731	2896	2000 and 2000	66.8 and 67.4
RAPS III and IV	2 x 220	711.6	2511	2000 and 2000	71.4 and 72
TAPS III and IV	2 x 540	2428	6100	2006 and 2005	61.5 and 50.6
Kaiga III and IV	2 x 220	3282	Not yet released	2007 and 2010	44.4 and 70.5
RAPS V and VI	2 x 220	3072	Not yet released	2010 and 2010	92.9 and 66.6

Sources: Costs from DAE 2002b, 32; CAG 1999; DAE 2005b, 35; Subramanian 2006c. Load factors and dates of commercial operation from the IAEA's PRIS database (downloaded August 2012). 1 crore = 10 million.

[†] Note that this 'original' cost estimate is much higher than the Rs 48 crore bid by General Electric. [*] This was derated from 200 MW. [#] The revised cost estimates for reactors commissioned after NAPS include interest during construction.

This improved performance of nuclear reactors must be balanced with the fact that similar improvements in performance have also been noted in many other sources of power. The average load factor in thermal power plants, for example, has increased from 54 per cent in 1990–91 to 69.97 per cent in 2001–02, and to 77.19 per cent in 2008–09 (CEA 2002, 2010). The performance of the plants run by the National Thermal Power Corporation (NTPC) has been significantly better; there was an increase from 70 per cent in 1992–93 to 81.1 per cent in 2001–02, to 91.1 per cent in 2008–09 (NTPC 2010).

The one reactor whose performance is not reflected in these statistics is the fast breeder test reactor. Though it does not produce much electricity, this is the only fast breeder reactor that the DAE has had experience with. Its performance should be important for anticipating the future performance of the DAE's reactors because the nuclear establishment envisions fast breeder reactors forming the basis of a nuclear-powered India. As Baldev Raj, director of IGCAR, stated when construction of the PFBR commenced, 'This PFBR technology will be the basis for generation of 500,000 MW, which will provide energy security to the country. The 500,000 MW will come through the fast breeder reactor route' (Subramanian 2004b, 103). But the PFBR and succeeding reactors are going to be built on the basis of experience with the FBTR. According to the DAE, the 'FBTR has provided valuable experience with liquid metal Fast Breeder Reactor Technology and the confidence to embark upon construction of a 500-MWe Prototype Fast Breeder Reactor (PFBR)' (DAE 2003c, 2).

As this chapter details, the FBTR's performance leaves much to be desired. That the DAE is going ahead with a massive breeder programme on the basis of this reactor suggests that the organization is unable to learn the appropriate lesson from past experience. It does not inspire confidence in the nuclear establishment's ability to come up with realistic technology assessments or sound selection procedures for future choices.

BOX 2.1

CRITERIA FOR SITE SELECTION

One problem that has intensified over the decades has been finding new locations for nuclear reactors, an absolute necessity for an ambitious programme. As the first nuclear power reactors were constructed, the DAE settled on particular criteria for choosing sites for reactors. These included a small or no population close to the reactor; proximity to cities or industries that could consume the electricity generated; the availability of water to cool the reactor; and the presence of appropriate soil structure and seismic conditions to reduce the risk from earthquakes (Meckoni and Mehta 1963; Rao, Kamath, and Ganguly 1963).

The rationale for these criteria is mostly self-evident. Meeting all these requirements at one and the same place has often proven difficult, and one or more have had to be diluted at each reactor site. There are even some in-principle contradictions: low population density and proximity to cities or industries, for example. Particularly difficult—given the high population density of the country—have been the criteria related to population distribution.

The criterion requiring low inhabitation near reactors comes from concerns about harm to public health caused by the small amounts of radioactive substances released by the reactor into the atmosphere during routine operations, and about the impacts of a catastrophic accident, should one occur. During the early days of reactor technology, there was no experiential basis for estimates on routine radioactive releases, let alone those that would result from a catastrophic accident. Therefore, the distance up to which habitation should be excluded, so as to avoid potentially high radiation doses, was chosen, somewhat at random, as one mile. When translated into kilometres, this becomes 1.6 km, seemingly more precise but just as arbitrary.

Eventually, all this became formalized into something called the code of practice for nuclear power plant siting put out by the Atomic Energy Regulatory Board (AERB 1990). This code requires that, in addition to an exclusion zone, with a radius of 1.5 km around the plant, there shall also be a sterilized area around the exclusion area covering an area of up to 5 km in radius around the plant. In this sterilized zone, the total population should be small, preferably less than 20,000. So that this may continue to remain the case, 'only natural growth of population is permitted' (GoI 2007, 140). The figure of 1.5 km results from 'rounding off' the 1.6 km (1 mile) radius and in some DAE documents both figures are used.[4]

There are, in addition, some 'desirable characteristics' for any reactor site, including: (i) a population density of less than two-thirds the state average in an area of a 10-km radius around the site; (ii) distance to population centres with a population of more than 10,000 to be more than a 10-km radius from the site; and (iii) population centres with a population of more than 100,000 to be at a distance of more than 30 km from the site.

The sterilized zone, according to the nuclear establishment, is the one at risk of extensive radioactive contamination in case of a major accident. To put that in perspective, in the aftermath of the Chernobyl accident, a zone of radius 30 km from the reactor was defined as the exclusion zone, and all the inhabitants in that area evacuated (UNSCEAR 2000, 472).[5] But the area that was defined as contaminated, because it contained the radionuclide caesium-137 in excess of 37,000 becquerels/sq. m, extended to more than 146,000 sq. km in Belarus, Ukraine and the Russian Federation alone. In March 2011, when the Fukushima accidents were in progress, the US Nuclear Regulatory Commission's Chairman asked US citizens living within a distance of 50 miles (80 km) to move (Sanger, Wald, and Tabuchi 2011).

Despite this potential for massive contamination, by the 1990s, as a way of making nuclear power economical, the Nuclear Power Corporation was arguing for a 'reduction of [the] exclusion zone area' because it claimed to have developed safer nuclear reactor designs (G.R. Srinivasan 1998, 17). The DAE would also like to build the advanced heavy water reactor (AHWR)—a design that has never been built anywhere in the world—in the Visakhapatnam campus of the Bhabha Atomic Research Centre (Subramanian 2012). The city of Visakhapatnam has a population of 1.7 million according to the 2011 Census.

There is yet another factor that increases the risk of the impact of a potential accident: population growth rates tend high in the vicinity of reactor sites since nuclear reactors do provide employment to a number of people—both directly and indirectly. Close to the Tarapur Atomic Power Station (TAPS), for example, the population density in the 1980s was over 247 per sq. km and the growth rate was 22 per cent, significantly higher than the state's rural average of 17.6 per cent. The sterilized zone was 'far from being devoid of human habitation' and had 'the highest density' in the vicinity of TAPS (Remedios and Sita 1989, 75).

A separate economic criterion utilized in site selection in the early years was that reactor locations should be far away from coal deposits. All through its history, the DAE has claimed that nuclear power was cheaper than thermal power in areas far away from coal mines (see [6] The strategy adopted by the DAE is to make nuclear power seem competitive by increasing the cost of transportation of coal. In recent years, however, this criterion seems to have been abandoned due to a combination of the DAE's demand for new reactor sites, especially coastal ones, and various state governments trying to benefit from electricity being generated by projects funded by the Central government, including nuclear ones.

TARAPUR

In January 1967, a boat set sail from Alameda, California, carrying about 41 tonnes of enriched uranium fuel (Baroch 1968, 1174). A similar shipment followed in September. Together, the total value of those shipments was reported to be over US$ 14.4 million. Both the boats headed to Tarapur in Maharashtra, the site of the first of India's reactors that would generate electricity.

Tarapur, located about a hundred kilometres north of Bombay, was a small fishing village with a population of a few hundred people when two prospectors, M.R. Srinivasan of the DAE and M.N. Chakravarti, then working for the Western Railway, arrived in 1959 (M.R. Srinivasan 1990, 6). Their aim was to take a closer look at the point on the coast north of a lighthouse near the village that Srinivasan and others had selected as a potential site for India's first nuclear reactor. The road to the village was so bad that the car carrying them broke down. From Tarapur, the two went towards the site by the only possible means of transportation—bullock cart. Even that did not get them to the actual site and the last little bit had to be covered on foot. But the experience did not deter the prospectors from recommending the site.

Meeting simultaneously with all the criteria for site selection laid down by the DAE (see Box 2.1 on criteria for site selection) was difficult even in the case of the first power reactor. As one of the most industrialized regions in the country then, the area between Bombay and Ahmedabad was considered ‘the most logical region to begin’ the ‘utilization of atomic power’ (Chakravarti and Srinivasan 1963, 458). In addition to Tarapur, three other locations that were considered in some detail were Umbergaon in Maharashtra, and Kakrapar and Navsari in Gujarat (Rao, Kamath, and Ganguly 1963, 305). The Gujarat sites were eliminated in the first of two rounds of selection. The Navsari site’s problem was that its soil was ‘water-logged, sandy and loose, with a topping of salt’. Kakrapar had two problems: a population of nearly 3000 people who were within the exclusion area and its proximity to a ‘large source of water supply used for drinking and intense cultivation right from take-off through a length of nearly 60 km of feeder canals’ (Rao, Kamath, and Ganguly 1963, 310). Umbergaon had the advantage that no one lived within the exclusion zone of the reactor but was eliminated in the second round because water for cooling the reactor was available closer at Tarapur.

Having gone through this exercise, the DAE announced in August 1960 that Tarapur was the chosen site. As is common with development projects in India, those who lived within the exclusion zone had to give up their houses (Sundaram, Krishnan, and Iyengar 1998, 104). Those displaced were from two villages: one tribal and the other non-tribal. While the government took some pains to relocate the non-tribal people, the tribal people were pushed to a far-off area (Bhat 1969). There they turned bitter about the fate that they had to accept for ‘the greater common good’.[7]

At the time of selecting the site, the DAE had not yet decided on what reactors it was going to install there. As described in chapter 1, the original expectation was that the reactors there would be British. There was no uranium enrichment capacity in the country and so the tender that was put out called only for reactors fuelled with natural uranium. But at the explicit request of US manufacturers, reactors fuelled with enriched uranium were also considered (Sundaram, Krishnan, and Iyengar 1998, 104).

The nuclear industry in the US was dominated by two companies: General Electric and Westinghouse. Both were aggressively competing for the top position as vendors of nuclear reactors, Westinghouse with its pressurized water reactor design and GE with its boiling water reactor

(BWR) design. As a way of upstaging Westinghouse, GE offered its first BWR prototype with what came to be called a ‘turnkey contract’: the buyer is sold the finished article at a fixed price, with the vendor accepting total responsibility for nuclear plant construction and start-up, and the utility having only to turn the proverbial key to start generating electricity (Pringle and Spigelman 1981, 163).[8] Over the next decade, as Westinghouse started offering its reactors on similar terms, this sales incentive became an important feature in persuading reluctant power utilities in the US to enter the nuclear business. Practically all of them were failures and the two companies took upwards of a billion dollars in losses (Burness, Montgomery, and Quirk 1980, 188). But that was all in the future, and in 1960, GE tried the technique to enter what they assumed would be a large Indian reactor market.

The turnkey bid from General Electric for the Tarapur plant was cheaper than even the optimistic expectations of the DAE: while the anticipated cost for a 300-MW reactor was Rs 510 million, GE offered 380-MW (two 190-MW reactors) for Rs 480 million. Buy more, spend less, as advertisements in US-style supermarkets would have it. What they didn’t predict then was that the actual cost of the reactor would nearly double to Rs 929.9 million (DAE 2002b, 32).

Even then, when counted along with the fantastically cheap loan that the US offered, the reactor has proven to be the cheapest among all the DAE was to build. The loan amount of about US$ 80 million was routed through the US Agency for International Development (USAID), and constituted the foreign exchange component of the project expenditure (Chellaney 1993, 26).[9] The forty-year loan carried a low interest rate of 0.75 per cent, with no payment requirement for the first ten years. Another long-term American credit of about US$ 14.4 million was provided to pay for the import of Tarapur’s first fuel loading. Thus, the *New York Times* was justified in describing the plant as ‘financed mostly with U.S. aid and … built by the International General Electric Company’ (NYT 1970b).

The actual building of the reactor was, however, done by the Bechtel Corporation, whose record of constructing reactors has been spotty. In San Onofre Unit 2, a nuclear plant that Bechtel was involved in constructing around the same time, the company installed the reactor vessel back to front

(Taylor, Buderi, and Kane 1982). The Palisades nuclear plant in Michigan, another reactor engineered by Bechtel, broke down shortly after it started operations. The Consumers Power Company that purchased the plant sued Bechtel and the two agreed to a US$ 14 million settlement. A Bechtel-designed reprocessing plant in New York State had repeated leaks of radioactive effluents. It was shut down in 1972 after six years of troubled operations and is now being cleaned up by the US federal government at an estimated cost of US$ 4.5 billion (von Hippel 2007, 30). Bechtel's construction work in Tarapur may well have been responsible for some of the reactor's eventual problems.

Construction work at Tarapur began in 1964. The following year, the troubles began with workers going on a strike for many months (Sundaram, Krishnan, and Iyengar 1998, 105). Two unions—the Indian National Trade Union Congress and the Hind Mazdoor Sabha—were involved.[10] The strike ultimately became violent and some workers, reported variously as seven and ten, died in police firing (M.R. Srinivasan 2002, 58–59; FE 1966; cited in Perkovich 1999, 503). Around the same time, the 1965 war between Pakistan and India started, and a ship carrying two steam generators for the Tarapur power stations was stuck in Karachi port (Sundaram, Krishnan, and Iyengar 1998, 105). The war ended soon but the steam generators had gone missing, never to be traced. Then, in 1968, several US reactors of the same kind as the one that was being built at Tarapur reported that cracks were developing in the inner lining of the reactor vessel, the structure that is intended to keep the radioactive fuel within it even if there were to be a disastrous accident. When the Tarapur vessels were examined, they were found to have similar cracks. The repairs took nine months. In 1969, then, when the reactor was finally commissioned, there must have been a huge sigh of relief from the DAE.

For General Electric, the year 1969 was memorable for a different reason. Earlier that year, GE workers went on strike demanding higher wages. True to its traditional bargaining strategy—characterized by a labour leader as 'telling the workers what they are entitled to and then trying to shove it down their throats'—GE offered a contract package and told the union negotiators to 'take it or leave it'. This strategy had worked earlier but, this time, conditions were different: inflation was running high and in many places workers had come out in opposition to the Vietnam War. The unions refused GE's offer and went on strike. After over a hundred days of coordinated effort, the strikers managed to bring GE back to the bargaining table in early 1970 and won a new contract. Termed 'one of the key strikes of our time' by labour historian Thomas Brooks, the 1969 strike marked a major turn in labour relations in the US.

Bechtel would also eventually have reason to remember 1969: it was the year that President Richard Nixon appointed George Shultz his Secretary of Labor (Pearce 2003). The relevance of this appointment for the Tarapur reactors was to become clear only a decade and a half later. During his next term as President, Nixon appointed Shultz his Secretary of the Treasury. In May 1974, when Nixon's Watergate scandal was at its height and impeachment hearings began, Shultz quietly moved out to become executive vice-president of the Bechtel Corporation, rising eventually to the position of vice-chairman of the Bechtel Group. He stayed with Bechtel till 1982 when he became Secretary of State under President Ronald Reagan. As Secretary of State, Shultz used his position to help resolve a dispute over spare parts for the Tarapur reactors, and the US issued an assurance that it was 'prepared to take the necessary actions to supply those parts which are not available from elsewhere' (Taubman 1983, A4; Kux 1994, 395).[11]

On 19 January 1970, some months after the Tarapur reactors started operating, Prime Minister Indira Gandhi came down to 'dedicate' the reactor to the nation (Mittal, Ramamurty, and Bhattacharjee 2006 & 2007, 22). The DAE made much of Tarapur being 'the largest operating nuclear power plant in Asia' (DAE 1970, ii). One and a half decades later, the DAE was still proudly announcing that TAPS was 'the first nuclear power station in Asia outside the Soviet Union when it was commissioned in 1969' (DAE 1985, 17). That is true, of course, but it does little justice to the history of TAPS after commissioning, which could be summarized in three words: problems, problems, problems.

These problems affected more than just the nuclear reactor. As a result of various technical problems in the reactor, Tarapur had to be shut down frequently. At that time, the Tarapur reactors were the largest electricity producers in the western part of India (Mittal, Ramamurty, and Bhattacharjee 2006 & 2007, 22). As a result, the western electricity grid, which was very unstable to start with, would itself go down, and the entire region would be without power. In turn, that would lead business leaders and industrialists to complain to politicians. In order to maintain political support, the DAE would try to restart power generation by the reactors, whether or not the technical problems had been adequately resolved.[12]

To come to the technical problems, there was repeated cracking in the stainless steel pipes and feed water nozzles used in the reactor (Katiyar and Bajaj 2006, 887). There were problems because guide tubes on which fuel assemblies normally rest moved out of position (DH 1972). There were corrosion problems from the use of seawater for condensing steam after it drove the turbine. There were frequent failures of mechanical seals used in the pumps that circulate water (Katiyar and Bajaj 2006, 887). There were leaks in the secondary steam generators.[13] Because of leaks, water in the secondary cycle would become radioactive as well. Each time these leaks had to be fixed, workers were exposed to high levels of radiation and accumulated large radiation doses (Mittal, Ramamurty, and Bhattacharjee 2006 & 2007, 22). There were problems with refuelling (that is, periodic removal of old fuel and addition of new fuel) because two internal components—the fuel spacer and the fuel orifice—would get dislodged from their specified positions (Katiyar and Bajaj 2006, 888). This is only a partial list, and, as of 2006, over 500 modifications have had to be carried out (Mittal, Ramamurty, and Bhattacharjee 2006 & 2007, 24).

In 1985, the secondary steam generators were isolated, that is, they were not used, and the power level was lowered to 160 MW (Katiyar and Bajaj 2006, 886). Not that anyone who relied on the DAE's annual reports for information about the performance of its reactors would have known. Neither the 1984–85 nor the 1985–86 report mentions that the power level was reduced, and that less electricity was being fed to the grid. The latter, for example, only records that TAPS II 'achieved an availability factor of 92 per cent and a capacity factor of 84 per cent during the year 1985. The corresponding figures for Unit-I are 71 per cent and 62 per cent, respectively' (DAE 1986, 2.2). It does not reveal that these factors were calculated on the basis of reduced power ratings, and the same measures would be much lower if the original power ratings were taken as the desired level.

Even after their power ratings were reduced, TAPS I and II performed relatively poorly. As shown in Table 2.1, their load factors have been about 62 per cent. This was after the lower power ratings had been taken into account; at the original power level, the load factor would be considerably less. One reason for the poor performance was the disruption in the exchange of nuclear information with the US. It is possible that if such information had been available, the performance of TAPS I and II *might* have been comparable to that of Oyster Creek, a BWR that also started operating in 1969 in the state of New Jersey. The cumulative load factor of the 650-MW Oyster Creek reactor is about 70 per cent—at the original power level.

Tarapur I and II reactors also experienced a period of uncertainty in the late 1970s over fuel supplies following the 1974 nuclear weapon test and the 1978 US Nuclear Non-Proliferation Act (see [14] However, diplomatic efforts and commercial interests prevailed, and France, China and Russia have stepped in as suppliers at various times. In the US, both the Carter and the Reagan administrations contributed to ensuring that the Tarapur reactors did not have to be shut down for lack of fuel.

BOX 2.2

MIXED OXIDE (MOX) FUEL

In the 1970s, the DAE started experimenting with using fuel assemblies that were made of MOX (Mixed Oxide, or a mixture of plutonium and uranium oxides). According to the DAE, investigations on refuelling TAPS with plutonium were completed in 1972 (DAE 1973, 86). In 1979, soon after the US decided not to supply fuel to the reactor, AEC Chairman Homi Sethna announced that, within three years, the DAE would develop MOX fuel as a substitute for enriched uranium (GAM 1979). By November 1982, however, an agreement for fuel supply was signed with France, and the first consignment arrived in May 1983 (DAE 1984, 11). But the promise of MOX was to persist and in 2001, the AEC chairman reportedly claimed: ‘Should there be any difficulty, we can still run the reactors using our MOX technology’ (Subramanian 2001b, 83).

The DAE’s assertions notwithstanding, MOX can only be a partial solution for fuelling Tarapur. Technically, it can be used because plutonium-239 has properties somewhat similar to uranium-235. So, instead of the increased uranium-235 content of LEU, MOX fuel will have an increased amount of plutonium-239. But plutonium-239 is *not identical to* uranium-235 and there are some important differences.

Two kinds of neutrons are released when an element like uranium-235 or plutonium-239 undergoes fission: those that are released immediately—prompt neutrons—and those that are released after a little while—delayed neutrons. The delayed neutrons are very important for safety and allow the reactor to remain under control in the event of small fluctuations in power level or temperature. When there are fewer delayed neutrons, there is less time for the reactor to be shut down in case of an accident. Compared to uranium-235, plutonium-239 gives out fewer delayed neutrons. Because of this key difference in the neutronic properties of uranium and plutonium, those reactors around the world that use MOX fuel typically—though not always—allow only a maximum of a third of their core to be loaded with MOX (Nagano, Sakurai, and Yamaguchi 1995). Thus, unless it is decided to compromise on safety requirements and increase the risk of accidents getting out of control, the use of MOX will only reduce the enriched uranium requirements, not eliminate it altogether.

The substitution of enriched uranium fuel with MOX might not only increase the probability of a severe accident, but also the hazard to public health. Should there be a catastrophic accident, resulting in the release of large quantities of radioactive materials into the atmosphere, the consequences would be worse for the inhabitants of the regions that experience radioactive contamination. This is primarily because greater quantities of plutonium—which is far more radioactive and injurious to health than uranium—would be released (Lyman 2001). MOX-fuelled reactors also have higher chances of fuel elements failing and releasing radioactive fission products into the water that cools the reactor because they typically operate at higher temperatures. The DAE's publications on MOX pay no attention to the dangers to public health and environment that might result from utilizing MOX fuel in reactors (Balu, Purushotham, and Kakodkar 1998; Kamath, Anantharaman, and Purushotham 1999).

Tarapur also houses two more recent reactors. TAPS III and IV are currently, as of September 2012, India's largest reactors and are designed to generate 540 MW of electricity. Unlike TAPS I and II, these are PHWRs that are scaled up from the design of the RAPS reactors imported from Canada. There are both parallels and differences between these reactors and the PHWRs currently constructed by the AECL. For example, the TAPS III and IV reactors use a fuel design with thirty-seven elements just like the AECL's reactors. On the other hand, the AECL reactors have much higher power ratings than those of TAPS III and IV.

TAPS III and IV were to be among the reactors to be constructed as part of the DAE's 1984 profile that envisioned 10,000 MW by 2000. If the TAPS I and II reactors were somewhat delayed, TAPS III and IV took much longer to go from the planning and procurement stage to construction. The financial sanction for the project was issued by the government in 1990–91 (DAE 1991a, 1.3), while advance procurement was initiated as early as 1985–86 (DAE 1986, 2.4). But the first of these reactors came online only in May 2006 (Subramanian 2006c).

Again, the project resulted in the displacement of those who lived on the land acquired for the reactors (ENS 1997). Two villages, Akarpatti and Pofran, had to be cleared. An estimated 3000 families were affected; many, including forty-one tribal (adivasi) families, were not on the original list of families counted by the government as being affected by the project (Jamwal 2005, 22). In 1989, Ram Naik, the newly elected member of Parliament from the Mumbai North constituency, decided to take up their cause (ENS 2006). After a long and tough fight lasting sixteen years, there was some success: in 2006, 348 farmers who had lost their land to TAPS III and IV received a total of 210 hectares.

The cost of the TAPS III and IV reactors was also much higher than the initially estimated value of Rs 24.28 billion (CAG 1999). The last estimates of the cost were about Rs 61 billion (Subramanian 2006c). The cost increase was kept under control, in part because the government extended large concessions to mega projects (Standing Committee on Energy 2002).

Tarapur III and IV were to be the only reactors of their kind. According to the DAE, 'future [pressurized heavy water reactors] … are planned to be only of 700 MW unit size' (DAE 2005a, 26).

RAJASTHAN

As far as producing nuclear electricity in India goes, the Rajasthan Atomic Power Station, not Tarapur, was the most significant reactor imported into the country. The bulk of the operating reactors in India are pressurized heavy water reactors (see Appendix 1 for description), and the first of these was RAPS I. The reactor and the location are known by many names: some talk about the Rajasthan reactors; others call it Rawatbhata after one of the nearby villages; yet others refer to the location as Kota, after the nearest town. Again, several sites, including Tuslo-ka-Namla, Faizpur and Maharajpur, had been examined, and Rawatbhata was selected because it was located in a low-population-density area and had assured water supply from the Rana Pratap Sagar Dam (Rao, Kamath, and Ganguly 1963, 310–11).

The design adopted for RAPS I was that of the first CANDU (Canada Deuterium Uranium) reactor at Douglas Point in Ontario. At that point, Atomic Energy Canada Limited, the Canadian nuclear agency, had gained experience only in constructing small experimental reactors. In 1959, it decided that it would build a 200-MW reactor so as to compete with other countries that were ahead in the game: the UK, which was constructing 300-MW Magnox reactors, and the US, which was constructing 200-MW light water reactors. It had not even decided on a design and was weighing ‘many, many ideas coming from all directions around the world’ (AECL 1984). Even after the design was completed, it turned out that ‘there were thousands of little snags and bugs to straighten out’. Construction of the reactor was delayed and Douglas Point started commercial operations, that is, supplying steady electricity to the grid, only on 28 September 1968 (Whitlock 2005).

Thus, at the time when the agreement between AECL and AEC was finalized in 1963, no reactor of this design had been constructed. Naturally, there was no way of knowing how easy or difficult it would be to operate the reactor. One of the seemingly attractive features of the Canadian heavy water reactor design was that it allowed used fuel to be removed and new fuel to be added even while the reactor was operating.[15] While the idea was elegant, the refuelling machines used in the process proved to be ‘no end of trouble’ (AECL 1984). There were other problems that Douglas Point encountered.

The relevance of these for RAPS was primarily that there was no operational feedback from the reference reactor at Douglas Point available to the designers of RAPS (Gopalakrishnan 2002). Building a reactor based on an unproven design resulted in many of the problems faced in some of the DAE’s PHWRs. As we shall see in the case of plans for breeder reactors, the DAE is all set to repeat the same mistake of constructing more reactors without feedback from operating the first reactor of a certain design for several years at the very least.

But all that was in the future. The Canadians were quick to start work, with construction of the reactor beginning in 1964, the year after the agreement was signed. In addition to the reactor, half of the fuel for RAPS I was also supplied by Canada (Graham and Stevens 1974, 29). When construction started, the expectation was that the reactor would start operating in 1969 (Sundaram, Krishnan, and Iyengar 1998, 112). But construction was delayed and, by 1968, the DAE was estimating that the reactor would start in 1971 (Tomar 1980, 522). Eventually, it was only in December 1973 that the reactor was declared commercial (Mittal 2004).

The causes for delay were many (Sundaram, Krishnan, and Iyengar 1998, 112). One was a fire inside the reactor building. Another was the cold Canadian winter, which resulted in delays in shipping reactor components. A third reason had to do with a safety feature called a dousing tank that held a large quantity of water which could be used to cool the reactor building in the event of an accident. But as construction proceeded, cracks in the support structure of the dousing tank were discovered and had to be repaired.

The last-mentioned problem is one example of an important conundrum of safety: adding further safety features might lead to new accident possibilities, often not envisioned earlier. In the event—albeit remote—that the cracks had not been discovered, or that they had developed later, after the reactor had started operating and then had propagated fast, it is possible that the dousing tank could have come crashing down, setting off further failures that could lead to a catastrophic accident. Even if such an accident has not happened, a different kind of problem did occur with the dousing tank in December 1980: a spurious signal led the control system to think that an accident was under way, and about two million litres of water stored in the dousing tank was released (Sundaram, Krishnan, and Iyengar 1998, 114). Many components were submerged and it took forty days for the reactor to be dried and to resume operations.

RAPS II took much longer than RAPS I even though it was similar in design. The project had received a financial sanction from the government in 1967 but plans began clashing with reality almost from the very beginning. Part of the problem was that, in order to conserve foreign exchange, much of the manufacturing was sought to be done locally. But even identifying manufacturers for the various components and persuading them to undertake the task proved difficult. Then there were what might be termed infrastructure issues. A good example was the reactor vessel. It took two years to resolve the first problem—that of finding a manufacturer. Then it took another four years for the vessel to be manufactured. Bringing the vessel to the site proved another source of delay because floods during the previous year had washed away a section of the road to Rawatbhata. And finally, obtaining the requisite quantity of heavy water proved a problem (see chapter 5). The reactor finally became operational in 1980.

A different set of reasons for the delay related to the labour force. When its reactors were being built, the DAE hired a large number of construction workers, but once the reactor had been completed, the DAE was unwilling to keep them employed. In Rajasthan, however, there was a substantial presence of unions, in particular, the Confederation of Indian Trade Unions (CITU) that was affiliated with the Communist Party of India (Marxist), the Hind Mazdoor Sabha that was affiliated with the then Jan Sangh, and the Indian National Trade Union Congress (INTUC) that was affiliated with the Congress party (M.R. Srinivasan 2002, 89). Among other things, they demanded non-retrenchment of surplus labour. The DAE refused and a long strike resulted. Eventually, the DAE moved many of the workers to other ongoing construction projects, such as the nearby heavy water project at Kota, and the more distant Madras and Narora Atomic Power Stations.

RAPS I was frequently down for repairs. The main cause was something called the end shield, which provides radiation protection to personnel involved in fuelling the reactor. In 1981, one of the end shields developed a crack and cooling water leaked out into adjacent areas (G. Ghosh 1996, 29). The reactor was shut down but the leak could not be plugged for more than four years, and the DAE even considered permanently closing down the reactor (K.S. Jayaraman 1986, 9). All through the 1980s, a series of measures was undertaken and the reactor restarted, but on each occasion, new cracks appeared (G.M. Taylor 1990b, 46–47). Finally, the reactor power was lowered to 100 MW and restarted in 1992 (Mittal 2004).

By far the biggest repair operation undertaken on the RAPS reactors was the replacement of the pressurized coolant tubes inside which the fuel elements are kept and into which the coolant—heavy water maintained at high pressure so that it does not boil—flows. The material initially used to make these coolant tubes was zircalloy, which, as the name indicates, is an alloy containing zirconium, but with some tin, iron, chromium and nickel added. As time passed, faced with high levels of radiation and heat, these tubes began to sag (Gopalakrishnan 2002). This led to local blistering and eventual rupture at the Pickering-2 reactor in Canada on 1 August 1983 (AECL 1997, 246).

Though the nuclear industry had understood since the 1960s that zirconium coolant tubes would corrode, and that irradiation often increased the corrosion rates, no action was taken in reactors that used zirconium coolant tubes till the Pickering accident. In the case of RAPS, the DAE had assumed that these coolant tubes would operate safely for at least sixteen 'Full Power Years', that is, as long as it would take the reactor to produce as much energy as it would during sixteen years at the maximum power (Mittal 2004, 90). But after the accident it was reassessed to be eight to ten years.

Following that accident, the Canadians started using another alloy in which 2.5 per cent of niobium is added to zircalloy. After nearly a decade, the same solution was implemented by the DAE in all reactors after Kakrapar II, which was commissioned in 1995 (Bajaj and Gore 2006, 705). In the Rajasthan reactors, the coolant channels were eventually replaced and the reactor restarted in 1998 (Bohra and Sharma 2006, 839). However, the 'degree of quality control and reliability are questionable', according to the former head of the Atomic Energy Regulatory Board (Gopalakrishnan 1999a).

About seven hundred metres from the first two RAPS units are RAPS III and IV (G.M. Taylor 1990a, 54). These received government approval in 1987, and the Hindustan Construction Company was chosen to undertake the civil works (M.R. Srinivasan 2002, 154). By speeding up construction, for example, by installing equipment while the reactor building was still being erected, it was hoped that the reactors would come up much faster. Originally estimated to start commercial operations in 1994 and 1995, they finally became commercial in June 2000 and December 2000, respectively (Bohra and Sharma 2006, 839).

Perhaps because of the distinction of being a part of the first site with four reactors, RAPS III and IV were 'dedicated to the nation' by Prime Minister A.B. Vajpayee in March 2001 in a ceremony attended by a galaxy of public persona: Anshuman Singh, the Governor of Rajasthan; Vasundhara Raje, minister for small-scale industries; Suresh Prabhu, Union minister for energy; Pradhyuman Singh, minister of finance for Rajasthan state; former chief minister of Rajasthan Bhairon Singh Shekhawat; AEC Chairman Anil Kakodkar; former AEC chairmen Raja Ramanna, P.K. Iyengar, and M.R. Srinivasan; and the top personnel of NPCIL (Nagaich and Sarkar 2000, 24). The show of force may have also been intended to balance the negative publicity given to the 1998 nuclear weapon tests in nearby Pokhran.

The plan in the early 1990s, as part of the 1984 atomic energy profile, was to set up four more units of 500 MW each at the Rajasthan site. Two of these were expected to start commercial operations in October 1997 and two more in April 1998 (G.M. Taylor 1990a, 54). None of that happened. In 2001, the NPCIL decided to just construct two 220-MW units, RAPS V and VI (ToI 2001). The project received administrative approval and financial sanction from the Central government in March 2002 (*Nuclear India* 2002b). A few months later, a superintendent at RAPS announced that the two reactors were expected to be completed by 2006–07 (*Hindu* 2002). The RAPS V and VI reactors were finally commissioned in 2010.

In August 2010, the government gave administrative approval and the financial sanction for setting up two 700-MW pressurized heavy water reactors (RAPS VII and VIII). These are estimated to cost Rs 12,320 crore (PTI 2010a). Along with the reactors being constructed in Kakrapar, these will be the first of the 700-MW PHWR design that the DAE has adopted. This design allows for a limited amount of the coolant to boil and thereby extract more heat from essentially the same fuel elements as in the 540-MW design (S.A. Bhardwaj 2006, 861). Such an increase will have implications for safety because there are significant increases in parameters such as steam pressure and flow.

KALPAKKAM

Madras Atomic Power Station

With the western part of the country 'served' by the Tarapur reactors, and the northern part of the country 'served' by RAPS, it was time for the southern part of India. The eastern part of the country was out of the running then because that part of the country had large coal deposits. For the third site, there were at least five competitors, two each from Tamil Nadu (then known as Madras State) and Andhra Pradesh, and one from Karnataka (then known as Mysore). These were Billigundlu and Kalpakkam in Tamil Nadu, Sangam in Mysore, and Somasila and Utukur in

Andhra Pradesh (Rao, Kamath, and Ganguly 1963, 312–13). Utukur ran the risk of being regularly flooded and was therefore eliminated. Based on public health and safety considerations, the remaining were ranked in the following order of preference: Billigundlu, Sangam, Kalpakkam, and Somasila, mostly based on typical wind conditions. In Kalpakkam, for example, the wind blew in the direction of areas with high populations for about 15 per cent of the daytime and 10 per cent of the night.

All locations had populations, ranging from 150 in the case of Billigundlu to 9600 in the case of Kalpakkam, who were resident in the exclusion and sterilized zones. Fishing was a major source of livelihood at three of the sites, Kalpakkam topping the list with an estimated annual catch at 500 tonnes. The region around Kalpakkam was also a major salt-producing region, and the nearest set of salt pans, about 16 km from the site, used to turn out about 1800 tonnes every year. Kalpakkam also had the maximum area under cultivation within 8 km of the reactor site.

Kalpakkam, therefore, had a lot of factors going against it. But, ultimately, the reactors' need for large quantities of cooling water, about 3190 million litres of water per day, according to the DAE (1970, 82), trumped all other considerations. Billigundlu, Sangam and Somasila were all inland sites, and a reservoir capable of storing adequate amounts of fresh water would have had to be constructed. And so, it was Kalpakkam that was selected to be the first site in southern India and home of the Madras Atomic Power Station (MAPS).

Over the decades, in addition to the heavy water reactors, MAPS I and II, the location has also become home to a pilot-scale fast breeder reactor, a reprocessing plant, a radioactive waste treatment (immobilization) plant, and a nuclear submarine testing facility. An industrial-scale fast breeder reactor, the PFBR, and its associated reprocessing and plutonium fuel fabrication plants are being constructed (AERB 2006). Two more industrial-scale fast breeder reactors are to be located at the same site (*Hindu* 2007b).

The feelings of the locals towards these were made clear during the first-ever public hearing to discuss the environmental impact assessment for a nuclear project. The hearing, a mandatory requirement under the Environmental Impact Assessment Notification, had been postponed twice before being conducted in July 2001 (Sri Raman 2001b, 2001a). At the meeting, conducted by a reluctant DAE, plans for constructing the PFBR evoked protests (Manikadan 2001). Of the nearly thirty members of the public who presented their views at the hearing, only one supported the project (DOSE 2001, 5). There was reason for this opposition. Different local groups have been negatively impacted in different ways. For example, fishermen complain that several varieties of seafood are no longer found in the vicinity of the reactor and that local people don't eat the fish caught in that area, forcing them to go sell their catch in Chennai (Shivakumar 2008; Chugoku Newspaper 1992, 187–88).[16]

When the project began, this may not have been envisioned. All that planners thought about was the prestige that reactor construction would bring to the institution. MAPS was expected to 'mark another milestone in India's technological development as it will be wholly Indian-built with almost 80 per cent indigenous content' (DAE 1970, ii). The basic features of the MAPS reactor were the same as those of the Rajasthan reactors, though with some modifications. One of these modifications was the installation of an underwater (submarine) tunnel to bring in water from the sea (M.R. Srinivasan 1970, 186). This seawater is used to cool the condensers, where the steam used for turning the turbines is cooled and converted back to water. The reason for having to install such a tunnel—unnecessary for RAPS—was that the east coast of India is characterized by large quantities of sand and silt—about a million tonnes a year—being moved across by waves, what is called littoral drift in technical parlance. Thus, if seawater were to be drawn in from too close to the coast, it would come with large quantities of sand and silt.

This solution in turn led to a new problem once operations had commenced. As the seawater came in, so did various debris and some living organisms, including jellyfish. The quantities involved were considerable, sometimes nearly twenty tonnes per month (Masilamoni et al. 2000, 568). This caused blockages, and at times forced the plant to be shut down, as in 1987; reactor operators have responded by continuously pumping large quantities of chlorine into the sea to try and poison all the living organisms (Rajagopal et al. 1996). This could be one factor responsible for the diminished catch that fisherfolk have experienced in the vicinity of the reactor.

Even constructing the tunnel was not without its problems. There were no ships that could carry the necessary heavy construction equipment and enter the shallow regions of the sea where the tunnel was to be built (M.R. Srinivasan 1970, 187). Therefore, it had to be constructed from the land—not an easy task. The other major factor to be contended with, just as in the case of RAPS II, was the lack of ability of Indian industries at that time to fabricate the necessary reactor components. A third problem was transporting heavy equipment to the site. The state government chipped in and improved the road from Chingelput (now Chengalpattu) to Sathurangappattinam; it also laid a new road from Sathurangapattinam to the project site and a bridge over the Buckingham Canal (DAE 1969, 80–81). But all this took time.

These were predictable problems, and it must have been obvious that dealing with them would take time. But the DAE was confident that 'the execution of [the MAPS] project will act as a pace setter' (M.R. Srinivasan 1970, 189). This prediction proved prescient: MAPS did set the scale for time and cost overruns. MAPS I and II were delayed by nine and eleven years, respectively, with the final cost figures of Rs 1188.3 million and Rs 1270.4 million, respectively, being roughly twice that of the initial cost estimates of Rs 617.8 million and Rs 706.3 million (DAE 2002b, 32). Some of the later reactors were to be even more delayed and experience higher cost escalations.

When the reactors were completed, they were 'dedicated to the nation' in typical fashion by the prime minister, but because they began operating in two different years there were two different people occupying that position. MAPS I was synchronized to the grid by Indira Gandhi on 23 July 1983 (DAE 1984, 11). But the signs were not good; in fact, they were ominous. Early that morning, oil had soaked into some insulation material that was in contact with hot pipes, and a fire had started (M.R. Srinivasan 2002, 115). Barely fifteen minutes after the fire had been extinguished, various activities required for restoring the reactor completed, and the reactor restarted, the prime minister arrived by helicopter. After the usual formalities were over, everyone had partaken of lunch, and Indira Gandhi was boarding the helicopter, there was a loud expulsion of steam, and the reactor tripped.

MAPS II, for its part, had the honour of hosting Rajiv Gandhi on 16 December 1985 (DAE 1986, 2.3). Unlike its twin reactor, MAPS II did not seem to have any problems then. But MAPS I had two major outages in that same year (1985) and the reactor had to be shut down because of vibrations in the turbine generators. This required the manufacturer, Bharat Heavy Electricals Limited (BHEL) to collaborate with General Electric Company, UK, and carry out modifications which resulted in lower vibration levels (DAE 1986, 2.3).

Both reactors have had troubled operating histories. In 1987, a number of blades of the turbine generators of both reactors broke and the reactors had to be shut down (DAE 1987a, 1–3). When the blades were examined, several cracks were discovered. These were supplied by BHEL, which was also supplying blades for other reactors. The DAE therefore diverted ‘components from turbines of Narora and Kakrapar to rehabilitate the two units of MAPS’ and argued that this was ‘one of the benefits of standardized designs and components in a number of units’ (DAE 1987a, 1–3). The benefit comes with costs: the same problem can occur simultaneously in a number of units. Thus, for example, following the accident in the Narora reactor (see chapter 7), many reactors had to be shut down to fix the problem with turbine blades that led to that accident.

Like the TAPS and the RAPS reactors, the MAPS reactors also had to be operated at lower power levels. In this case, it resulted from the failure of the moderator inlet manifold, which diffuses the low-temperature heavy water used to moderate neutrons as it flows into the calandria (G. Ghosh 1996, 30). Because the flow of the moderator was affected, both reactors had to be run at a lower power level of 170 MW as compared to the original 235 MW (Gopalakrishnan 2002, 379). It was over a decade before major repairs could be carried out and the capacity of the MAPS reactors increased to even 220 MW in 2006 (IAEA 2007, 2008b).

Of the two units, the MAPS II reactor has performed better. It has had several more years of operation with load factors in excess of 80 per cent. But, with MAPS I and II having cumulative lifetime capacity factors of 49 per cent and 55 per cent respectively, neither reactor can be said to have achieved a high overall level of performance.

The Fast Breeder Test Reactor

The part of Kalpakkam taken over by the DAE was home not just to MAPS and those who worked on it, but also another team that was engaged in 'friendly competition'—and in constructing the fast breeder test reactor (M.R. Srinivasan 2002, 248). Though the FBTR does not produce much electricity, it inaugurated the second stage of the three-stage nuclear programme, on which long-term and large-scale nuclear power production in India is contingent, according to the DAE. Thus, its history is as important as that of any power reactor.

When the budget for the FBTR was sanctioned in September 1971, it was anticipated that the reactor would be ready by 1976 (CAG 1993). Like many other reactor projects, this one was delayed. When it first became critical in 1985, the net time overrun had become 220 per cent, and the corresponding increase in cost had gone up by 164 per cent—from the originally proposed Rs 348.5 million to Rs 919.8 million. Even then, the reactor was not fully functional and the steam generator, essential for producing electricity, began operating only in 1993 (Hibbs 1997b, 10). This electricity, about 0.5 MW, was fed to the grid only in 1997 (Kapoor 1997).

Originally, the FBTR was supposed to be constructed using more or less the same design as the French reactor Rapsodie. The primary fuel to be used in the core of the reactor (see section on fast breeder reactors in Appendix 1) was a mixture of plutonium and uranium oxides with the uranium enriched to 85 per cent in the uranium-235 isotope (B. Raj 2005, 36). That idea vaporized along with French support after the 1974 nuclear weapon test, and the DAE settled on a mixture of plutonium and uranium carbides, with plutonium constituting about 70 per cent of the initial (Mark I) core.

This change also meant that the power rating of the reactor had to be reduced. The FBTR was initially designed to produce 40 MW of heat. Of this power, only 13.2 MW would be converted to electricity by the turbines. Thus, its power specifications are written as 40 MWt/13.2 MWe. But till 1992, it was operated at 1 MWt; the operating level went up in steps till it reached 17.4 MWt in 2002 (Srinivasan et al. 2006, 804), and it appears to have stayed at that level (Raj and Chellapandi 2011, 205). Nonetheless, the FBTR's power level is still often listed—misleadingly—in DAE publications as 40 MWt (see, for example, Bhoje 2000; DAE 2003c, 2).

Not only was the reactor much delayed, but for most of the first one and a half decades of the FBTR's life, operations were tarnished by several accidents of varying intensity. Two of these are described here in some detail since they illustrate the complexities of dealing with even relatively minor accidents at fast breeder reactors, and the associated delays as well as the hazards they pose to workers. When viewed in combination with similar experiences elsewhere, they suggest that it is unlikely that breeder reactors will ever perform with high reliability.

In May 1987, there was a major event that took two years to rectify (Srinivasan et al. 2006, 803–04). This occurred as a fuel subassembly was being transferred from the core to the periphery (Kapoor et al. 1998, 152). The problem began with the failure of a logic circuit involved in the rotation of the plug to move the selected fuel assemblies. For some reason, this logic circuit was bypassed and the plugs were rotated with a foot-long section of one fuel subassembly protruding into the reactor core. This resulted in the bending of that specific subassembly as well as the heads of twenty-eight reflector subassemblies on the path of its rotation. Various manoeuvres to rectify the situation did not help; they only resulted in one reflector subassembly at the periphery getting ejected and a 'sturdy guide tube' getting bent by 32 cm. The last event has been described as the result of 'a complex mechanical interaction', which suggests that how it happened was never really understood.

All these mishaps required extensive repairs before the reactor could be restarted. First, the guide tube had to be cut into two parts using a 'specially designed remote cutting machine' while ensuring that no chips that came out during the cutting process fell into the core (Srinivasan et al. 2006, 804). Then, the damaged reflector subassemblies had to be identified using a periscope. The periscope was needed because sodium is opaque (see section on fast breeder reactors in Appendix 1); this reflects the operational difficulties associated with the use of molten sodium. Finally, part of the sodium had to be drained out and the damaged subassemblies removed using specially designed grippers. All this took time, and reactor operations commenced only in May 1989.[17]

The second accident is common in fast breeder reactors—a sodium leak. That this leak occurred seventeen years after the reactor was commissioned underlines its generic nature, and how difficult it is to eliminate the occurrence of such accidents. The leak occurred in September 2002 inside the purification cabin which houses the pipelines of the primary sodium purification circuit (Sasikumar, Krishnamachari, and Ramalingam 2003, 4). The cause of the leak was said to be 'the defective manufacturing process adopted in the manufacture of the bellows sealed sodium service valves' (Kapoor 2002, 14). By the time the leak could be confirmed and controlled, about 75 kg of sodium had spilled over and solidified on the cabin floor and over various components of that cabin.

Removing this radioactive sodium was a major effort. To begin with, even to approach the cabin, the workers had to wait ten days to allow for a reduction in the radioactive activity from the sodium, some of which would have absorbed a neutron to become sodium-24, an emitter of dangerous gamma rays. Even after the ten-day period, in areas near the spilt sodium, the hourly radiation dose to workers was as high as 900 millisievert (see Box 8.1 on radiation and health in chapter 8).[18] Another problem resulted from the fact that the whole cabin is normally surrounded by a layer of nitrogen so as to avoid the burning of sodium. At first, IGCAR tried simply to replace the nitrogen with regular air so that clean-up workers could breathe. But this led to sparks and fires involving the spilt sodium. These had to be put out with dry chemical powders—but then this resulted in lots of dust being suspended in the atmosphere and making the visibility poor. The upshot was that nitrogen had to be reintroduced and workers were sent in wearing masks that had a tube which fed them with air to breathe. Much of the work had to be done remotely which, while lowering the exposure to radiation, made it a very slow operation. In all, removing the relatively small quantity of 75 kg of sodium and bringing the cabin back to normal conditions took about three months (Sasikumar, Krishnamachari, and Ramalingam 2003, 6).

One result of these two accidents, and many more, was that it took fifteen years before the FBTR even managed to operate at full power for more than fifty days continuously (R. Prasad 2001). Over the first twenty years of its life, the FBTR has operated for only 36,000 hours or 75 days a year (DAE 2006b, 16), implying that the availability factor was only about 20 per cent. Based on this chequered history, IGCAR claims to have 'successfully demonstrated the design, construction and operation of a FBR under Indian conditions' (Rodriguez 2000, 2). Such an assessment does not inspire confidence in the organization's ability to learn nor does it lead one to expect efficient performance by larger breeder reactors.

The Prototype Fast Breeder Reactor

Even before the FBTR went online, the DAE started making plans for a larger prototype fast breeder reactor and persuading government policy makers about these. According to the 1974 Fuel Policy Committee (FPC) report, construction of the first commercial fast breeder reactor was to start in 1978 and the reactor was to start operating by 1986, with three more similar ones to be added by 1990–91 (FPC 1974, 89). Such an aggressive schedule set out in one of the important energy policy documents of the government might seem surprising. But, as a prominent energy analyst observed, the Fuel Policy Committee 'seems to have compromised its judgement with the aspirations of DAE in projecting a very rapid growth of nuclear power beyond the period 1982–83 without substantiating the rationale for this' (T.L. Shankar 1985, 85).[19]

A year after construction was to have started, the DAE set up a steering group, which submitted its first report in July 1980 and a supplementary report in November 1980; this was followed by the DAE setting up a PFBR Working Group in March 1981 to prepare a feasibility report (Bhoje 2006, 2). Following the setting up of all these groups and their reports, the DAE requested the government for budgetary support in 1983 (Bidwai 1983). The first expenditures on the PFBR started in 1987–88 (DAE 1991b, 34). In 1990, it was reported that the government had 'recently approved the reactor's preliminary design and has awarded construction permits' and that the reactor would be online by 2000 (Hibbs 1990, 11).

The reactor design that the DAE came up with involved the use of mixed plutonium–uranium oxide as fuel in its core, with a blanket of depleted uranium oxide that would absorb neutrons, and transmute into plutonium. Liquid sodium would be used to cool the core, which would produce 1200 MW of thermal power which, in turn, would be used to generate 500 MW of electricity. The remaining heat would be released into the surrounding environment, mostly in the form of hot water expelled into the sea.

Even this minimal design information should point to the differences between the FBTR and the PFBR. For example, the FBTR used a fuel based on mixed plutonium–uranium carbide rather than the oxide variant used in the PFBR. At the time when the DAE was planning to embark on the construction of the PFBR, there wasn't much experience even with the FBTR. And, as the Atomic Energy Regulatory Board pointed out, the FBTR had not even started operating at full power (NEI 1991, 4). The AERB maintained that work on the prototype would be premature if it were to be undertaken prior to adequate experience with the FBTR.

This made a lot of sense. There was no point in starting work on a bigger reactor when the small pilot one wasn't working well. What's more, if one were to go by experiences with reactors like the Superphénix in France and Monju in Japan, constructing the PFBR merely on the basis of experience with the FBTR would still be premature. Consider, for example, the history in France. Designed on the basis of experience with both the pilot-scale Rapsodie reactor and the Phénix, a 250-MW demonstration reactor, the 1240-MW Superphénix became critical in September 1985, but went into commercial operation only in April 1987 because of internal oscillations and the failure of a turbo-generator (NUKEM 1997, 8). Since then, it was a long saga of shutdowns, one after the other. In May 1987, it was shut down due to a sodium leak. Full-power operations resumed only in June 1989, but in October 1989, the reactor was again shut down due to impurities in the primary circuit. It was restarted in April 1990 and resumed full-power operations in June 1990. In July 1990, the reactor was again shut down due to impurities in the primary circuit. In December 1990, the roof over the turbine hall collapsed due to a heavy snowfall, resulting in significant damage to the turbo-generators (NUKEM 1997, 9). The reactor restarted in August 1994 but at low power. It was only in September 1996 that the power was raised to 90 per cent of full power but the reactor was again shut down in December 1996.

Given this troubled history, the June 1997 announcement by the French prime minister that the project was to be abandoned should have come as no surprise.[20] In its eleven years of existence, the reactor produced 7.9 billion kilowatt-hours of electricity—equivalent to just 0.73 years of full-power operations, and a load factor of about 6.6 per cent. Going from the Phénix to the Superphénix represented scaling by a factor of five, as compared to nearly seventy in the case of the FBTR and the PFBR.

One of the differences between the FBTR and the PFBR is the coolant void coefficient, which tends to become positive in large reactors like the PFBR.[21] The concern about reactor designs with a positive coolant void coefficient became more prominent after the Chernobyl accident. The Chernobyl reactor also had a positive coolant void coefficient, even though its coolant was different from that of most fast breeder reactors, and that was one of the main reasons for the devastating 1986 accident (Hohenemser 1988, 388–89). As a result, nuclear engineers around the world have preferred reactor designs that have negative void coefficients. Going against that trend, the DAE came up with a design for the PFBR that has a relatively large and positive sodium void coefficient, roughly one and a half to two times that of similar fast breeder reactors (IAEA 2006, 48).

The reason for this choice in essence is that such a design would be cheaper since a reactor core with a lower void coefficient would require it to be smaller (so as to allow for the escape of neutrons) and thus will not benefit from economies of scale (Paranjpe 1992, 512). As we shall see in chapter 7, there are other design elements that the DAE has chosen for lowering costs, but which have the effect of further compromising safety. Despite these efforts, electricity from the PFBR will remain significantly more expensive than even electricity from the DAE's PHWRs.[22]

By the early 1990s, the DAE had decided that 'the capital cost of [fast breeder reactors] will remain the most important hurdle' to the rapid deployment of breeder reactors, a key element in its vision of a nuclear-powered future (Paranjpe 1991, 1.4–8). Therefore, during the nineties, as the FBTR struggled with operational difficulties and accidents, the DAE's work on the PFBR focused on 'design optimisation with an objective of minimising capital cost' (Bhoje and Govindarajan 2004, 54). As a result, the DAE claims that the 'primary objective' of the PFBR was 'to demonstrate techno-economic viability of fast breeder reactors on an industrial scale' (Chetal et al. 2006, 852).

In 2001, the chairman of the Atomic Energy Commission announced that the PFBR would be commissioned by 2008 (PTI 2001). Construction of the reactor was finally started in October 2004 and was initially expected to be commissioned in 2010 (Subramanian 2004b, 103). Less than a year after commencement of construction, and after the disastrous tsunami of December 2004, the director of IGCAR announced that the reactor would be completed eighteen months ahead of schedule (*Hindu* 2005a). The claim about completing the reactor ‘ahead of schedule’ was reiterated a year later by Project Director Prabhat Kumar (Subramanian 2006b). By 2009, the tone had changed slightly; Kumar was ‘confident’ that the reactor would start generating power sometime in 2010, but added: ‘There may be some surprises’ (IANS 2009). In May 2010, BHAVINI announced that the reactor would become operational in March 2012 (Subramanian 2010). The update from January 2012 was that the reactor would go critical in early 2013 but that would be followed by ‘a year of testing’ before it is declared commercial (IANS 2012).

The PFBR is to be the first of the many, many breeder reactors that the DAE envisions building over the next four decades. The ‘manys’ in the previous sentence are not typos: they reflect the hundreds of industrial-scale breeder reactors that are included in DAE projections for 2052, while it is yet to complete the construction of even the one that it has been planning since the 1980s. Like the heroine of *Alice in Wonderland*, one’s reaction to such pronouncements is to laugh and declare that one can’t believe impossible things. But, as the Queen replied to Alice, ‘I daresay you haven’t had much practice … Why, sometimes, I’ve believed as many as six impossible things before breakfast’. The DAE, for its part, has had plenty of practice putting up wondrous projections of an atomic-powered future in its nuclear wonderland, and so believes that by mid-century it will construct hundreds of reactors. This entire edifice will depend on how the prototype fast breeder does.

BOX 2.3

DUAL USE OR MISUSE?

During the course of negotiations over the US–India nuclear deal, a less-advertised reason for the DAE’s attraction to breeder reactors came out quite clearly. In what was an ostensibly civilian agreement, much of the DAE’s efforts were focused on optimizing its ability to make fissile material for the nuclear arsenal within various constraints, especially the shortage of uranium. One strategy that the DAE seems to have thought about was revealed indirectly because the institution focused a lot of attention on keeping the fast breeder program outside safeguards. In a prominent interview to the *Indian*

Express, the chairman of the AEC said, 'Both, from the point of view of maintaining long-term energy security and for maintaining the minimum credible deterrent, the fast breeder programme just cannot be put on the civilian list. This would amount to getting shackled and India certainly cannot compromise one [security] for the other' (Bagla 2006). The term 'minimum credible deterrent' is a euphemism for the nuclear weapons arsenal. Another misleading term is 'maintaining', which does not mean holding the number of weapons fixed, but instead means constantly increasing the size of the arsenal.

The relevance of fast breeder reactors for the arsenal is that they produce what is called weapon-grade plutonium. While all plutonium can be used to make nuclear weapons, weapons designers prefer plutonium with lower proportions of the heavier isotope plutonium-240. The blankets of breeder reactors, like the PFBR, produce plutonium with only a small percentage of plutonium-240. At the same time, reactor-grade plutonium, or plutonium with higher proportions of plutonium-240, is consumed in the core of the PFBR. The strategy that the DAE may be considering may be discerned from its resistance to classifying its reprocessing plants or its stockpile of reactor-grade plutonium as civilian. This allows for the possibility that breeder reactors like the PFBR are used as a way to 'launder' unsafeguarded reactor-grade plutonium—both the historical stockpile as well as future production at unsafeguarded reprocessing plants—into weapon-grade plutonium. The PFBR can generate about 140 kg of weapon-grade plutonium every year if it operates at a 75 per cent capacity factor (Glaser and Ramana 2007, 100). Such a strategy would increase the DAE's fissile material production capacity for weapons several-fold.

NARORA

The genesis of the choice of Narora as a location for a reactor was part of the DAE's attempt to make nuclear power cheaper. The general wisdom on capital-intensive sources of power—and indeed most kinds of industrial production—is that when the facility becomes larger, then there are economies of scale, and the unit production cost—whether of electricity or some other commodity—comes down.[23] But, unlike in Western countries, the DAE could not think of constructing large nuclear reactors. The problem, as Vikram Sarabhai, Bhabha's successor as chairman of the AEC, was to point out at the IAEA General Conference in September 1968, was that the electricity grid in India was small. In other words, the maximum amount of electricity that flowed through the transmission and distribution cables at any given time was small. A small grid becomes unstable, that is, susceptible to failures, if very large-sized generating units are added. So, all sources of power, whether nuclear or thermal or hydel, were constrained to be small. Therefore, the power they generated was 'twice as expensive as power used by industrially advanced nations' (Sarabhai, Meckoni, and Thomas 1969, 4).[24] This was particularly a problem for nuclear power because the primary component of generating electricity at these reactors was the capital cost.

Another feature of the electricity grid of that period was the wide variation between maximum demand and minimum demand. In the grid in northern India at that time, the peak or the maximum load was 1430 MW, but the minimum was 600 MW (Sarabhai, Meckoni, and Thomas 1969, 3). Since nuclear reactors, for technical reasons, cannot change their output easily and are best suited to generate a steady amount of power, they could not be used efficiently to supply power to such a grid. This limited the power capacity of the reactor. Thus, in the grid described by Sarabhai, it did not make sense to construct a nuclear reactor to generate more than 600 MW of power; if it did, there would be times when the extra power would have to be stored—requiring more expenditure in electricity-storage technology—or wasted.

But even a single reactor of 600-MW capacity would not make sense in this circumstance. That is because there would necessarily be times of the year when the nuclear reactor would have to be shut down for maintenance or, in some reactor types, to put in new fuel.[25] Even in very efficient nuclear reactors, this period is at least a couple of weeks every year or so. There would also be unexpected shutdowns due to, say, safety reasons. The low capacity factors in the DAE's reactors imply that such periods of shutdown are long and frequent. To avoid loss of power or blackouts, there would have to be one or more backup power plants capable of generating 600 MW. That would be expensive. A better solution, in the eyes of those interested in maintaining grid stability, is to build much smaller power plants.[26] Then, the periods when individual power plants are shut down for maintenance could be scheduled in such a way that only a small fraction of the total capacity would be out of service at any given point in time, and the backup capacity needed would be smaller. Electricity planners typically use a 'general rule of thumb that a grid should not be subjected to power variations in excess of 10 per cent of the total grid capacity' (Carelli et al. 2007, 654). In other words, from the point of view of grid stability, the largest nuclear reactor that would have been acceptable in the northern India grid of that time would be 140 MW. This was even smaller than the 220-MW reactors that the DAE was constructing.

Sarabhai's solution to this set of considerations reminds one of the proverb about Muhammad and the mountain. Rather than trying to make nuclear power meet with the electricity demand, the idea was to change the electricity demand to meet with the requirements of the nuclear reactor. To make the nuclear reactor fit into the grid, the grid would be expanded by adding many new demands for electricity. The question was what kind of demand to add.

Fortunately for the DAE, this was a problem—how to justify large nuclear reactors without upsetting grid stability—that others had grappled with. The most prominent of those who had tried to deal with this problem was Alvin Weinberg, director of the Oak Ridge National Laboratory in the USA. Oak Ridge was one of the original nuclear laboratories set up at the time of the Manhattan Project and it produced the majority of the enriched uranium that went into the first atomic bomb dropped on Hiroshima. The leaders of Oak Ridge were also amongst the early converts to nuclear power.

The Oak Ridge idea was to set up what was termed agro-industrial complexes powered by atomic energy (Weinberg 1967, 16).[27] Weinberg's idea was motivated by the fact that, during the same period when nuclear reactors were developed, various energy-intensive technologies had also been developed. The one that Weinberg focused on was the development of various high-yielding varieties of grains that were now being widely grown as a result of the green revolution. But they required large amounts of irrigated water and nitrogenous fertilizer. These demands, Weinberg argued, could be met through 'the energy-intensive technologies of extracting fresh water from the sea, and of manufacturing electrolytic hydrogen (and thence ammonia)' (Weinberg 1967, 14). The energy would, naturally, be generated by nuclear reactors and Oak Ridge scientists went around advocating this idea (Michel and Young 1967).

Soon after Sarabhai took over as chairman, the AEC nominated some engineers to participate in a study group at Oak Ridge (Mirchandani 1968, 211). The US nuclear establishment was only too happy to collaborate on this effort and, in late 1967, a team of American experts visited India to study the possibility of setting up nuclear-powered agro-industrial complexes. Looking around for potential locations where this experiment may be carried out, the Oak Ridge team settled on the Gangetic plain (Stout 1968). This research on nuclear-powered agro-industrial complexes in the Gangetic plain was sponsored, tellingly, by the US Atomic Energy Commission under contract with the Union Carbide Corporation (Young 1969, 9).

The working group that the AEC set up for studying a nuclear-powered agro-industrial complex submitted its preliminary report in June 1968 (DAE 1969, 52). The group studied two locales: one in the Kutch–Saurashtra region in Gujarat and another in the western Indo-Gangetic plain region. The idea was to commission two relatively large-sized nuclear reactors (600 MW each, about three times the power rating of the reactors at Tarapur and Rawatbhata) in each complex (AEC 1970, 18). The electricity generated would be used to pump water from tube wells, in the case of the Gangetic plain, or desalinate seawater in the case of Kutch, as well as manufacture fertilizers and fabricate aluminium.

In the event, none of these ideas materialized. As the histories of the Kalpakkam and Rajasthan II power plants show, the DAE found its hands full with just setting up 220-MW reactors. And soon, there was the fallout from the 1974 nuclear weapon test to deal with. There was an attempt to revive the idea of nuclear-powered agro-industrial complexes in the late 1970s (Ramachandran and Gururaja 1977, 381), but that wasn't successful, either. Plans to set up a nuclear reactor in Kutch were abandoned along with the larger scheme of a nuclear-powered agro-industrial complex.

The idea of an agro-industrial complex should be seen as a way for gathering support from a diverse set of constituencies.[28] Though it does reflect to some extent the differences between notions of development held by Sarabhai and the rest of the nuclear establishment, it did not constitute proof of the DAE's interest in providing alternate livelihoods for rural inhabitants. Rather, it was a demonstration of its concern that it would not be able to deliver on what it had originally set out to do, that is, produce cheap electricity for the existing grid. At other locations, the DAE tried to find different ways of garnering support by promising to fulfil needs specific to that region, and thereby build alliances with other groups.[29] Thus, for example, the perennial shortage of water in the city of Madras led the DAE to consider using the Kalpakkam reactors to also desalinate water;

unfortunately, their own studies showed that it would be much more expensive compared to other ways of obtaining water (Meckoni 1968, 352).

Though Narora had agricultural factors going for it, the chosen site had two problems. One was the very characteristic that makes the area so good for agriculture: the alluvial soil. Reactor buildings are very heavy and therefore a large load has to be borne by the soil. The foundation loading of a reactor building could be as high as 160 tonnes per sq. m, though only in some parts (Venkatesh and Sarma 1974). Since alluvial soil does not bear high loads well, especially when the loading is not uniform, a suitable rigid foundation capable of holding it up would have to be constructed; this would add to costs and time, both in the design and the actual erection of the reactor.

The alluvial soil compounded the second problem with Narora: it was an earthquake-prone region. In general, the DAE and the Atomic Energy Regulatory Board claim that 'nuclear plants are sited at locations that have low incidence of natural events such as seismicity, floods, high winds, cyclones, [and] heavy precipitation' (Chande 2003, 308). But Narora was 'located not far from known geological faults and epicentres of earthquake disturbances' (M.R. Srinivasan 2002, 123). Thus, it was entirely possible that the site might be subject to an earthquake at a future date.

The reason to be concerned about earthquakes is that they simultaneously affect large parts of the nuclear power plant, thereby increasing the likelihood of accidents. Nuclear establishments, however, claim that they have designed reactors in such a manner that they can withstand seismic shocks. Indeed, the former secretary of the AERB went so far as to declare: 'I know that the nuclear power plants are the most seismically hardened structures in the country. Only the ignorant will call me foolhardy, if I rush to a nuclear power plant to save myself from an imminent earthquake!' (Parthasarathy 2007a)

Is this assertion justified? The DAE, like nuclear establishments elsewhere, carries out analyses that evaluate the safety of nuclear reactors during earthquakes. These analyses typically begin by postulating some earthquake that is deemed the worst possible at that site, and then subjecting 'safety structures like [the] containment' to 'detailed seismic analysis' for the hypothesized earthquake (Bohra and Sharma 2006). But, because of various uncertainties, it is difficult to have high confidence in assertions about the worst possible earthquakes, a fact that is all too apparent after the March 2011 Fukushima accidents.

Why is there so much uncertainty? To start with, it is not easy to forecast —nor is there a foolproof way to do so—when an earthquake may occur or how intense it might be at any given site. One way this is done is by classifying areas into seismic zones, with zone numbers varying from I to V, with a higher number implying a higher likelihood of a more damaging earthquake. The Narora site was classified as zone IV (Jain and Nigam 2000). However, these seismic zone classifications are revised from time to time as more knowledge is gained about the geological features, in particular, the tectonic aspects, and any seismic activity (Murty 2004, 86). Future events may cause revisions of earlier assessments of the likelihood of earthquakes at a site. For example, following the September 2001 earthquake that struck various parts of Tamil Nadu, the Geological Survey of India decided that peninsular India might have to be categorized as zone III instead of zone II (Subramanian 2001a). More dramatically, two major earthquakes, at Koyna (1967) and Latur (1993), occurred in areas categorized as zone I, supposedly the safest, causing those areas to be revised to zone IV and III, respectively (Murty 2004, 86). Geologists also do not know of the existence of various seismic faults and 'unknown faults that cause damaging earthquakes are fairly common'; for example, the magnitude 6.3 earthquake that struck Christchurch, New Zealand, in 2011 occurred on an unknown and unexposed fault (Macfarlane 2011). Geological knowledge is constantly changing (Wald 2012), and this change is difficult to take into account when building expensive nuclear reactors with the expectation that they will be operating for several decades.

The second source of uncertainty is how a nuclear reactor may behave in the event of an earthquake. Take, for instance, what happened to the Kashiwazaki–Kariwa Nuclear Power Plant due to the earthquake that struck Japan on 16 July 2007.[30] Some of the known results of the earthquake included a fire and leaks of radioactive water (Ban and White 2007, 4). The larger implications and cause for concern came from a host of small failures that were completely unexpected (Ramana and Kumar 2007).

One example of a completely unexpected event was the manner in which radioactive water was released. The earthquake caused underground electric cables to be pulled down by ground subsidence, creating a large opening in the outer wall of the basement of the reactor—a so-called ‘radiation-controlled area’ that is supposed to be completely shut off from the outside environment (Miura 2007). In the words of an official from the Tokyo Electric Power Company, ‘It was beyond our imagination that a space could be made in the hole on the outer wall for the electric cables.’

In summary, constructing a nuclear reactor in an earthquake-prone zone compounds the inherent risk of catastrophic accidents and, hence, Narora was not a desirable site. Nevertheless, the DAE’s relentless search for new reactor sites led it ‘to locate the fourth nuclear power station at Narora in Bulandshahr District’ of the state (DAE 1973, 142). There was an additional, political consideration that favoured Narora—Prime Minister Indira Gandhi’s efforts to break into the stronghold of Charan Singh in Uttar Pradesh (D. Sharma 1983, 108–10). To underscore the political importance of the project, she herself visited the site to inaugurate the construction activities (M.R. Srinivasan 2002, 123).

By the time the Narora project began in earnest, countries like the US and Canada had mostly stopped nuclear cooperation with the DAE. Narora, therefore, relied heavily on the European countries. The design adopted for that reactor involved somewhat more complicated steam generators. While these were manufactured by BHEL, the ‘detailed designs and specifications’ were obtained from Kraftwerk Union AG (KWU) of Germany (M.R. Srinivasan 2002, 127). Other imports from Germany included primary heat transport pumps and certain parts for the steam generators, one result of which was that the DAE ‘could complete the steam generators for Narora earlier than if [it] had only depended on BHEL’; Spain and Sweden were also sources of other components, while French and Swiss companies performed quality control work (M.R. Srinivasan 2002, 130–32).

Despite these inputs from these countries, the Narora project was greatly delayed. The two reactors were originally projected for commissioning in 1977 and 1978 (AEC 1970, 16). In a statement to the Parliamentary Estimates Committee for 1977–78, the AEC chairman declared that the DAE’s targets were December 1981 and 1982 for Units I and II respectively, but that they ‘had some problems’, including getting land and cooling water (Mirchandani and Namboodiri 1981, 57). For a reactor located in a prime agricultural zone, that should presumably have been anticipated. Some years after these deadlines had passed, in April 1987, AEC Chairman Raja Ramanna announced that the first of the reactors was ‘scheduled to become operational in 1988’ (Ramanna 1987, 215). That expectation, too, did not materialize.

One further cause for delays was the several design changes being incorporated during construction (Bohra and Sharma 2006, 843). While this may be justified due to safety reasons, such changes could also be a potential source of safety problems. In a complex system like a nuclear reactor, changing one part could result in unforeseen impacts on another, especially during unusual operating conditions or accidents.

But even familiar systems might fail unless both design and operations are carried out with adequate diligence. This was not the case with BHEL, Trichy, which was manufacturing the steam generators for the project. Due to ‘a mistake in the design of the supporting steel work’, massive concrete slabs from the ceiling fell on top of some special drilling equipment (M.R. Srinivasan 2002, 127). The accident resulted in a delay of at least two years.

The last straw was that even after the reactors became critical, ‘the unit had initial teething troubles’ during the pre-commissioning period (Bohra and Sharma 2006, 840). Thanks to all these problems, Narora I started operating commercially only in January 1991, while the second unit went into commercial operation in July 1992. Less than a year later, the Narora power station was to have the most risky of nuclear accidents so far experienced in India (see chapter 7).

Narora was perhaps the first nuclear plant to face opposition (N.G. Raj 1989). One reason was the displacement of inhabitants from the exclusion area around the reactors. Another impetus for the protests came from urban activists who went around the area explaining the dangers of radioactivity, and the potential for a Chernobyl-type accident (which occurred while the plant was being constructed). The movement built up to the extent of mobilizing a group of fourteen members of Parliament submitting a memorandum to stay the commissioning of the reactor (Gadekar 1988, 46). But the reactor’s commissioning went on, even though it was delayed.

KAKRAPAR

Kakrapar was one of those sites that lost to Tarapur when the first nuclear plant was being set up. The reason given then was that there was a large population within the exclusion area and the site was close to a large source of water used for drinking and cultivation (Rao, Kamath, and Ganguly 1963, 310). Neither of those had changed. If anything, the population in the area had only increased, both naturally and because of various construction activities. By the 1980s, there were about 36,000 people within 5 km of the Kakrapar site (KAPS 1989, 45). But the DAE, always looking around for places to locate reactors, started arguing that the rapid industrialization of Gujarat had increased the demand for power (Sundaram, Krishnan, and Iyengar 1998, 120). That argument seems to have worked and, in 1980, the AEC announced that Kakrapar was to become the fifth nuclear power station (NW 1980, 12). The project received its financial sanction in July 1981 (DAE 1982, 7). One improvement was that the DAE set a more reasonable completion target of 1990–91 (NW 1981, 6).

In addition to the population, another problem with the Kakrapar site was that it was in a low-lying area, prone to flooding. This was of particular concern because the site was close to the Ukai Dam and it was conceivable that the whole reactor might get flooded. Within the DAE there were some who thought that this was an unlikely contingency, and not worth considering. But the design safety committee decided that it was a serious issue and insisted that a great deal of earth-filling be done (M.R. Srinivasan 2002, 139). How well that was done was seen in June 1994, when floodwater entered the condenser pit and the turbine building (see chapter 7).

If Narora had the problem of being in a seismic zone and on alluvial soil, Kakrapar had the problem of being in a seismic zone but on hard rock. The problem with the latter was that, unlike loose soil that dampens some of the seismic disturbances, the stiffness of the rock accentuates ground motions; this meant ‘a large investment in snubbers [that is, mechanical devices that limit the motion of, or absorb shocks to, equipment during an earthquake] for pumps, steam generators and other equipment.’ These were to be procured from ‘a limited number of suppliers, mostly in Europe and Japan, [who] could supply such anti-seismic attachments’ (M.R. Srinivasan 2002, 142).[31] The result was familiar—a delay in reactor commissioning.

Kakrapar was another of the DAE's nuclear power stations to undergo an accident even while it was under construction. In 1991, there was a fire in the switchgear room—the area from which power is transmitted to the grid—which, in turn, led to a failure in the functioning of various power supplies, including emergency diesel power generators that are supposed to kick in in the event of power failures (Gopalakrishnan 1999a). Fires have been a regular feature in the DAE's reactors; in 1990, just a year before the Kakrapar fire, the official count was more than a dozen (M.G. Joseph 2004, 76). There is thus a question mark over considerations of safety and learning from accidents. Even if none of these has led to a major radioactive release, they are costly—the Kakrapar fire of 1991 resulted in an estimated loss of Rs 100 million (ToI 1992, 7). Once again, there was a delay in commissioning the reactor. These delays notwithstanding, when compared to earlier reactors, Kakrapar was constructed relatively fast and KAPS I was commissioned in September 1992.

There were, however, some last-minute local concerns. Based on leaks by someone within the nuclear establishment, journalist Rupa Chinai (1992a) reported that KAPS I was being commissioned without 'integrated testing of the ECCS'.[32] The revelation prompted some activists—in particular the well-known Gandhian Narayan Desai to go on a fast and resort to other means of protest (Desai 1992). There were several opposition marches, with police firing in one case (Gadekar 1987b, 13). Despite the protests, the reactor was commissioned.

The DAE was quite proud of Kakrapar, a sentiment that was justified when, in 2003, KAPS I was declared the best-performing heavy water reactor in the world by the CANDU Owners Group (ToI 2003). In 1998, the DAE allowed a confidential peer review of Kakrapar by the World Association of Nuclear Operators (WANO), an organization formed by the nuclear industry after the disastrous Chernobyl accident as a way of learning from each other's experience.[33] Though advertised by the DAE as proof of its openness and safety, in reality, WANO's peer reviews are always kept confidential, and are never released to anyone outside the management of the reactor that hosts the inspection. Four years later, a leading nuclear industry journal reported that neither officials in the International Atomic Energy Agency nor the US Nuclear Regulatory

Commission ever learnt anything about the contents of the WANO Kakrapar report; it was *rumoured* that the report identified good points and bad, and concluded that 'operational safety and accident prevention were weaknesses' (Hibbs 2000, 11). The experience with WANO's inspectors seems to have been comfortable enough for the DAE to follow it up with a WANO review of the Narora reactor.

A few years later, though, there was another event that suggested that all was not well with the Kakrapar I reactor. According to the AERB, on 10 March 2004, there were failures of two of its key safety systems—the Automatic Reactor Power Control System and the Automatic Liquid Poison Addition System. The reactor power rose gradually from about three-quarters of the maximum, where it had been deliberately set, to close to full power (AERB 2004b). Investigations by KAPS and NPCIL lasting over a month could not identify the causes of the power increase and the unit had to be shut down. This shows how, in a nuclear reactor, because of the complex processes involved, the physical conditions that develop during its operation may never be fully comprehended, and the understanding which designers or operators of the reactor have would always be partial.[34]

Kakrapar is to be home to two more reactors—700-MW PHWRs, a design with which NPCIL has had no experience so far.[35] They received environmental clearances on 19 December 2006.

KAIGA

As with many others, Kaiga came to be considered as a potential nuclear site due to regional considerations. Both the north and the west of the country had two atomic power stations each, Rawatbhata and Narora, and Tarapur and Kakrapar, respectively. It was now the turn of the south and a search was mounted to identify a successor to Kalpakkam. The DAE's site selection committee looked at sites in Karnataka, Kerala and Tamil Nadu because these were the states that had a greater proportion of hydroelectric capacity (M.R. Srinivasan 2002, 148). One possibility was Bhoothathankettu near Kothamangalam in Kerala, but that idea was abandoned in the face of strong opposition (Varghese 2000, 321–31).[36] In Tamil Nadu, the Koodankulam site was selected.

Within the state of Karnataka, three sites were examined by the DAE's site selection committee: Kaiga, Tungabhadra and Narayanpur (Kati 1988, 5). According to the Nuclear Power Corporation, Kaiga was chosen because it was 'far from coal fields', there was 'no conflict in priorities in water use', was in a 'very low population zone', had 'good foundation conditions' and was needed 'for strengthening the western part [of] the southern region with baseload generation' (Kati 1988, 6). The last criterion may have tipped the balance in favour of Kaiga over Koodankulam, though the latter was to have its turn later.

What all these criteria missed out on was what struck most people about the location: the lush landscape that surrounds the site. Witness, for example, the description of the site by a journalist: 'Kaiga is situated on the bank of river Kali in the North Kanara district of Karnataka. It is about 40 km inland from the Arabian Sea where Kali debouches from deep gorges carved out of the steep west bank of the Western Ghats. It is bounded by steep hills on three sides with closed canopy forests nurtured by heavy seasonal precipitation' (Hegde 1988, 3). Another one says:

> The exact site where the reactors will come up … is designated in the records as 'minor forest' … Within a kilometre up the road in the ghats the minor forest gradually thickens, raises a canopy, and diffuses the sunlight—in places even blocking it out completely—so that even in the afternoon, one feels one is already approaching twilight. Trees rise to a height of more than 60 feet. Underneath, the dense growth prevents human access. (Alvares 1988, 10)

Kaiga was perhaps the only reactor in the world to be situated in a tropical rainforest, rich in biodiversity. In addition to the reactor, there would be transmission lines from the reactor to the demand centres to be built. There would be the infrastructure that comes with any development project, including roads and human habitation. Then, there would be the demands placed by the inhabitants on the surrounding areas through, for example, requirements for wood. The danger to this ecosystem was evidently not even part of the official set of considerations. But among civil society groups, the realization that such impacts would irreversibly alter the environment around Kaiga triggered a vigorous protest movement, which spread from the local area to the state capital of Bangalore.

A range of groups and individuals joined the movement. These included the Karwar Medical Practitioners Association, the Scientific Workers

Association in Mysore, the Fisherwomen's Cooperative Society in Karwar, the Karnataka Rajya Raitha Sangha, the Progressive Writers Union in Mysore and the Save the Westen Ghats Movement, to give but a few representative examples (Ramakrishna 1996, 164–65). Local government bodies such as the Uttara Kannada Zilla Parishad and several Mandal Panchayats in Karwar Taluk passed resolution against Kaiga.

The opposition to Kaiga also resulted in the first major legal challenge in the country to nuclear power. In 1990, the Samaj Parivartana Samudaya, a grassroots group from Dharwad, filed a public interest litigation case that went up to the Supreme Court (Sorab 1996, 158). The chief petitioner was the eminent Kannada writer K. Shivaram Karanth. The petition requested the disclosure of records of the case, directed respondents to invite suggestions and objections from citizens, and to carry out a fresh, comprehensive environmental impact assessment covering gaps as highlighted by the petition. The petitioner also directed respondents to draw up social and environmental security schemes for the project-affected people. On 7 May 1993, the Supreme Court directed the Central government, that is, the DAE, to 'take cognizance of … the petitions submitted on the question of re-siting the Kaiga plant' (Ramakrishna 1996, 168). In legal terms, this was a victory for the movement challenging the Kaiga plant, but in practical terms it meant little—the DAE simply maintained that they had taken into account the concerns of the petitioners and continued building the reactors.

Significantly, the judges in the case did allow one of the petitioners, Vishnu Kamath, and his counsel M. Rama Jois to inspect the EIA conducted by the National Environmental Engineering Research Institute (NEERI) at the office of the Department of Atomic Energy in the South Block, New Delhi (Supreme Court of India 1993).[37] The DAE, true to form, had refused to share any information on the environmental impact of the plants with the public. The Supreme Court overruled the DAE and directed it to show the EIA report to the petitioners. However, the petitioners could only read the report in the DAE office and make notes which, again, could be used only for the purpose of making a submission to the department for consideration. Even within these constraints, this aspect of the judgement was unprecedented and constituted a step towards requiring the disclosure of what was traditionally considered sensitive material (D.B. Rao 2009).[38]

The opposition led the government to organize a National Workshop on Nuclear Power at the Indian Institute of Science, Bangalore, in December 1988 with prominent leaders of the DAE as well members of civil society. The DAE more than met its match here, and found that many of its arguments in favour of nuclear power were taken apart by participants from civil society. For example, on the economics of nuclear power, it turned out that Amulya Reddy (1988), who argued that nuclear power was uneconomical, had used better methodology and more reliable data and, in general, done a more careful analysis, as compared to the DAE officials. Many participants in the workshop questioned the DAE’s secretive practices and lack of transparency. In response, AEC Chairman M.R. Srinivasan offered an amusing reason—though presumably in all seriousness—‘We have no objections to giving information. But giving all the information needs a lot of paper which we cannot afford’ (Gaur 1996, 93). Despite the clear and persuasive arguments offered by those opposing the Kaiga project, ultimately, the political clout of the DAE was greater.

The clout was also visible at the level of the Central government. In 1986, the Department of Environment had raised objections to some specific aspects of the Kaiga project (Bidwai 1987). These objections focused on the interpretation of an earlier clearance and the location of the housing colony. The DAE disagreed on both counts and the dispute remained unsettled for months. On 12 November 1986, Prime Minister Rajiv Gandhi informed Parliament that the decision with regard to Kaiga nuclear power plant had not yet been taken by his government (Bidwai 1987, 17). But, four days later, the DAE corrected him, saying that Kaiga had already been selected (Alvares 1988, 11). In other words, the DAE could essentially overrule higher political authorities, even on controversial decisions.

By the time the Kaiga project commenced, the Nuclear Power Corporation was seriously concerned about the time taken to construct a reactor. It therefore modified numerous practices to speed up construction, for example, accelerating the rate of pouring concrete by pumping it through pipes. The mechanical erection of heavy equipment, such as steam generators and transformers, was done as soon as the floor of the building was complete even though the full building had not been constructed (V.S.G. Rao 1994, 290). The NPCIL assured the public that its construction practices

> ensured … by strict adherence to the safety rules and regulations … at all stages of design, construction, operation & maintenance … The materials of construction, the raw materials for manufacturing of equipments [*sic*] and components as well as the manufactured items are all subjected to quality assurance. The tests are carried [*sic*] as per nuclear standards. The quality assurance is done both at the manufacturer [*sic*] premises as well as prior to the installation at the plant. (Kati 1988, 10)

That these assurances meant little was demonstrated on 13 May 1994 when part of the inner containment dome—the structure that is supposed to prevent the escape of radioactivity into the environment should an accident occur—of the first unit collapsed for no discernible reason. Numerous concrete slabs weighing an estimated 130 tonnes came crashing down from a height of about 40 m (Sundararajan, Parthasarathy, and Sinha 2008, 40). Illustrating its ability to put a harmless spin on even serious matters, the nuclear establishment came up with the term 'delamination' to describe this collapse. The dome was eventually reconstructed and, reportedly, used a construction code, or set of rules and specifications, called RCC-G developed in France (Basu and Gupchup 2004, 200). Five years later, after the construction of the containment dome of Kaiga I was completed, a fire broke out on it when sparks from a welding machine ignited paint tins, leading to a loss of Rs 3.5 million (ToI 1999a).

Even as the Kaiga I and II debate was under way, the DAE sought and obtained clearance for a further four reactors from the state government, the Union ministry of environment and forests, and the Atomic Energy Regulatory Board (DAE 1991a, 2.6; 1992a, 3.4). The financial expenditures on these reactors started around 1990 with the DAE ordering reactor parts that take a long time to be delivered. But soon afterwards, the DAE found itself short on Central government funds as the country embarked on an economic liberalization process. The DAE had already been allotted ample funding for completing the 1984 Atomic Energy Profile, but the construction costs of its reactors had ballooned dramatically.[39] The DAE then started negotiating with state governments and proposed constructing Kaiga III and IV as a joint-sector project, with NPCIL holding 51 per cent of the stake, and the states of Karnataka, Tamil Nadu, Andhra Pradesh, Kerala and Pondicherry holding the rest (DAE 1995a, 3.6). This effort does not seem to have succeeded and, in 1999, the AEC chairman was still bemoaning the fact that Kaiga III and IV were yet to get financial clearance from the government (DH 1999). Only in March 2001 did the main plant excavation start (NPCIL 2001). Kaiga III was completed in May 2007 (NPCIL 2008b), while Kaiga IV reached criticality only in November 2010.

In June 2012, the Union cabinet cleared NPCIL's proposal to set up two more units of 700-MW capacity in Kaiga (TNN 2012). This has been resisted by local villagers. Even prior to the cabinet announcement, representatives from these villages had met with Kaiga officials and expressed their strong opposition to any additional reactors (*Canara Times* 2011). Concern about accidents, especially after Fukushima, and impact on health from radiation and other pollutants seem to be major causes for this opposition (Raghuram 2011).

KOODANKULAM

Koodankulam is at the southern tip of India, barely 20 km from Kanyakumari and across the water from Sri Lanka. In the 1980s, it was selected as a potential nuclear reactor site by the DAE selection committee. Following the DAE's not being allowed to construct any reactors in Kerala due to public opposition,[40] the relative proximity of Koodankulam to Kerala and, therefore, the possibility of supplying nuclear power to two states, became an additional attraction (*Hindu* 2007c). Typically, the DAE did not take into consideration the fact that the site lies at the edge of the Gulf of Mannar, one of the world's richest marine biodiversity areas. Among the Gulf's 3600 plant and animal species are the globally endangered sea cow (dugong) and six mangrove species endemic to peninsular India (UNESCO 2001). The hot water discharged after cooling nuclear reactors is likely to affect adversely this precious biological reserve. The three coastal districts abutting the reactor site account for the majority of Tamil Nadu's fish catch.

When the site was selected, it was going to be just another site for the DAE's 'long-term programme of nuclear power expansion' (M.R. Srinivasan 2002, 149). But that was not to be. During approximately the same period as the site selection process was being conducted, some members of the DAE had been pushing for importing reactors from the Soviet Union. But successive AEC chairmen Homi Sethna and Raja Ramanna were opposed to the idea (M.R. Srinivasan 2002, 182–85). It was only when M.R. Srinivasan succeeded as AEC chairman in March 1987 that the idea gained momentum.

On the Soviet side, there was great interest in selling a reactor to India, in part to highlight the close relationship between the two countries. The idea dates back to at least 1979 during Prime Minister Morarji Desai's visit to the Soviet Union when Premier Alexei Kosygin offered to supply a reactor to India (Moody 1997, 115). The offer was reiterated in 1982 when Prime Minister Indira Gandhi visited Moscow.

The Soviet Union had never exported nuclear reactors to any country except the Soviet Bloc countries. The chances of any country's being interested in a Soviet reactor plummeted after the 1986 Chernobyl accident, resulting in the Soviet Union putting greater pressure on and making a more attractive offer to India. The hope was that a nuclear deal could be announced as a notable example of increased Indo-Soviet economic cooperation during President Mikhail Gorbachev's visit in November 1986 (Moody 1997, 116).

The Soviet Union bent over backwards to secure the Koodankulam deal. To start with, it did not insist that India sign the Nuclear Non-Proliferation Treaty and put all its nuclear facilities under international safeguards (M.R. Srinivasan 2002, 190–91). Then, it agreed to support the enriched uranium required to fuel the reactors over their entire operating life, thereby allowing those in India interested in importing a Soviet reactor to persuade those in opposition that a Tarapur-like situation would not occur. It even seemed to have agreed to take back all the radioactive spent fuel produced in the reactors. And finally, it agreed to a loan package with a low interest rate of 2.5 per cent per annum.

The DAE and the political leadership of the country were persuaded by these inducements and, in November 1988, Prime Minister Rajiv Gandhi and President Mikhail Gorbachev signed an intergovernmental agreement for two 1000-MW VVER-1000 reactors to be constructed in Koodankulam.[41] This led to the first wave of protests from local inhabitants. In December

1988, a month after the agreement with the Soviet Union was signed, a massive rally was organized at Tirunelveli by the ‘Samathuva Samudaya Iyakkam’ (Social Equality Movement) and other groups (Srikant 2009). Matters came to a head on 1 May 1989, during a demonstration in Kanyakumari involving over 10,000 participants, organized by the National Fish Workers Union, when the police opened fire and disconnected the PA system. But that catalysed further demonstrations and meetings. This movement was the forerunner of the massive protests seen in 2011–12.

In 1988, VVER-1000 reactors were still very new and there was little operational experience with them.[42] There was thus a parallel with the experience of importing RAPS I on the basis of the untested design of Canada’s Douglas Point reactor. When they were built and had been operating for a few years, VVER-1000 reactors started developing what came to be called the sticking control rod problem (Thomas 1999, 749–50). During operation, the control rods—which absorb neutrons and are used to shut down a reactor—became deformed. As a result, they could not be inserted into the core within the prescribed time; some got totally stuck. Further, at that time, Soviet safety standards did not reflect any lessons learnt from the Chernobyl accident.

VVER-1000 reactors that were constructed elsewhere in the late 1980s and 1990s have had persistent control rod problems. In the Czech Republic, the Temelin-I reactor started operating in 2000 and, by June 2006, there were fifty-one control rods that could not be inserted properly (Kastchiev et al. 2007, 42). Similarly, at the Kozludoy-V reactor in Bulgaria, there was a serious problem on 1 March 2006. Due to electrical failure, one of the four main pumps used for circulating water tripped. The system automatically reduced the power but three control rod assemblies remained in the upper-end position. Follow-up tests on the remaining control rod assemblies identified that twenty-two out of sixty-one could not be moved. Control rod insertion failures are considered very serious and increase the likelihood of small, initiating events leading to a severe accident.

All in all, if a VVER-1000 had been imported at that time, it would have almost certainly given much trouble. But, with the disintegration of the Soviet Union in 1991, the project went into cold storage. By 1993, the chairman of the AEC admitted that instead of VVER-1000s from Russia, he was ‘very keen on building two reactors of 500 MW each’ at Koodankulam but that financial resources were not available (Chidambaram 1993, 100).[43]

It was only in 1997 that the project was reconsidered (*Hindu* 1997). This coincided with troubles in the Russian nuclear industry. In 1999, for example, the *New York Times* reported that one company that operated twenty-nine nuclear power plants in Russia lacked money to pay workers, perform maintenance and repairs, inspect crucial pipes, and even buy fuel (Wald 1999). This was because the federal government was cutting back on funding for the nuclear energy ministry (Pomper 2009, 3). One way to deal with these cutbacks was to find export markets and the revival of the Koodankulam project fit into that effort.

Russia again offered the reactors on generous terms. In addition to a guaranteed lifetime supply of enriched uranium fuel, it offered a loan for 54 per cent of the cost at a sub-market interest rate of 4 per cent per annum, repayable in fourteen equal annual instalments starting one year from the commissioning date (Gopalakrishnan 2002, 392). On the basis of this agreement, the construction of Koodankulam I and II reactors started in September 2001. At that time, the reactors were expected to be commissioned in December 2007 and December 2008 (MoSPI 2008, 21). But like all other reactors, this did not happen.

The opposition seen in the late 1980s resurfaced soon after the project was revived. In November 2001, S.P. Udayakumar from Nagercoil and his friends founded a broad umbrella organization called People’s Movement against Nuclear Energy (PMANE). Their main focus was public education. Over the years, they visited numerous villages and towns in the neighbouring districts and talked to concerned citizens, women’s associations, fishermen’s associations, farmers’ associations, student groups, teachers and religious leaders. In 2003, over 7000 people from the three districts of Tuticorin, Tirunelveli and Kanyakumari came together in a massive rally against the reactors (Srikant 2009, 8). There was, however, no public forum where they could submit a formal complaint to the government.

One such forum was to present itself a few years later. Even before the construction of Koodankulam I and II started, NPCIL started talking of establishing more reactors at the same site.[44] One difference between I and

II which were under construction and the proposed units was that, in 1994, the government came out with the Environmental Impact Assessment Notification, which was subsequently replaced with a revised one in 2006 (see Appendix 3 on the EIA process). In the case of Koodankulam I and II, NPCIL insisted that, although construction had started only in 2001, the project had been approved in 1989 and so did not have to go through the EIA process.[45] That excuse could not be used for the proposed expansion. Therefore, NPCIL commissioned NEERI to conduct an EIA study for Units III to VI.[46] This was completed and published in March 2004 (NEERI 2004).

In 2007, as part of the EIA process the authorities had to organize a public hearing. I was requested by a local group to help them understand the EIA document, which had been released to the public. When I read through the report, I found that it had numerous problems. Specifically, its assessments of damage were not reliable, and it did not consider the full range of potential impacts. An example of the first kind is what the EIA assumes about the quantities of radioactive gases that will be discharged into the atmosphere during routine operations. The EIA's assumptions are much lower than the corresponding figures for VVER-1000 reactors elsewhere. iodine-131 is one of the radioactive gases released into the atmosphere by many nuclear reactors. If this ends up in the body, through food or milk that is contaminated, the radionuclide tends to accumulate in the thyroid, causing cancer. Indeed, the most prominent health impact of the Chernobyl accident so far has been a dramatic increase observed in cases of thyroid cancer among the exposed population (UNSCEAR 2000, 497–504, 514). For Koodankulam III to VI, the iodine-131 discharge for each reactor is given as 248,000 becquerels per day (NEERI 2004, 3.9), which is less than one-sixth the discharge rate for another VVER-1000 reactor (Khmelnitsky-1) located in Ukraine. It is smaller, by a factor of 7.4, than the discharge rate for the Rovno 3 VVER-1000 reactor, also in the Ukraine. The release rates for what are called noble gases are even smaller: twelve and twenty-three times, respectively. These discrepancies between roughly identical reactors suggest that the data used in the Koodankulam EIA are not dependable.

Based on these unreliable figures, the EIA concludes that the 'annual dose of inert radioactive noble gases, iodine and long-lived nuclides in the form of particulates will be well below the stipulated standards' (NEERI 2004, 3.5). Even if the guesses about atmospheric release rates are correct, this latter assertion is baseless as NEERI has not collected any data to assess the radioactive dose that would result from each unit of radioisotope released. That is because people are exposed to radiation through multiple routes. In the vicinity of most nuclear facilities, there is radioactive contamination—though typically at relatively low levels—of air, water and soil. People may, therefore, accumulate radiation doses from breathing this air, drinking this water and eating food that is grown on this soil or is irrigated with this water. The same will be true of the fauna in the region, including fish, cows and goats.

Therefore, to estimate how much radiation a local inhabitant would be exposed to, the EIA should have started by collecting data on people's consumption levels of milk (since that is a major vehicle for iodine doses) and locally grown food. Then, it should have estimated the radiation levels which would be present in them by standard transport pathway analysis. Finally, it would have had to put the two together to predict radiation doses to people who would consume the local food products. The EIA presents no evidence of having carried out such an analysis. Local grassroots organizations confirm that people in the vicinity of the plant have never been surveyed about their diet or lifestyle (Udayakumar 2008). At a non-nuclear level, the EIA report deals with the issue of the impact of thermal discharges without reference to the project being situated in an ecologically sensitive habitat.

An example of the second kind of problem, that is, impacts not considered, pertains to the potential environmental contamination that may come from the spent fuel that will necessarily have to be stored on site for several years in order that it may cool. The spent fuel contains the bulk of the radioactivity that leaves the reactor and yet the EIA does not mention what is to happen to this spent fuel, nor does it evaluate the potential environmental impacts of storing this spent fuel while it is cooling, much less what might happen in the event of an accident. Instead of focusing on such critical issues, the EIA elaborates on trivia like noise levels during the construction stage of the project.[47]

This was the EIA put out for comments. But when it came to actually listening to the public, NPCIL tried hard to avoid it, postponing it thrice. Facing the public is something about which the nuclear establishment has always been reluctant. And in the context of getting a clearance from the MoEF, the DAE was doubly reluctant. In 2005, the DAE had suggested to the MoEF that some of its projects be exempted from any public consultation requirement (Menon and Ramana 2007, 18). If there had to be public hearings, DAE officials demanded that they be limited to project-affected people and those whom it considered 'genuine professionals'. In other words, activists and NGO personnel, who often are the best informed about these projects outside the nuclear establishment, were to be denied an opportunity for any input. Shortly thereafter, in 2006, the EIA Notification was indeed amended to limit participation in public hearings, and researchers have subsequently been rejected from presenting their views at hearings.

When the public hearing was finally held in June 2007, several thousands of people from all over the Tirunelveli, Tuticorin and Kanyakumari districts came in trucks and buses to the Government College of Engineering in Tirunelveli, only to be confronted by an intimidating bundobust—1200 policemen in riot gear, tight security cordons and armoured personnel carriers. Further, the room assigned for the hearing could accommodate only a small fraction of those who wanted to have their voices heard. The approximately 800 participants who were allowed to come into the room had numerous questions, such as 'How will the spent fuel from the reactors be disposed of?' They had complaints, such as 'The EIA report should have been made available in Tamil to the public.' Or, they simply wanted to register their opposition to the project. The overwhelming majority of those inside, and the several thousands who waited outside the room because of lack of space, declared that they did not want the project.

As participant after participant spoke against the Koodankulam plan, the official in charge abruptly announced that NPCIL had clarified all the people's doubts, and declared the meeting closed (Menon and Ramana 2007, 17). Many of those with questions or comments—including me—did not have an opportunity to speak. I did manage to hand over a written submission that laid out the abovementioned problems with the EIA (and got a signed receipt), urging that the EIA document be rejected as flawed and inadequate for project clearance (Ramana 2007b).

Contrary to the requirements of the EIA Notification 2006, the minutes of the meeting—which would be entered into the official record as the views of the public—were neither read out nor validated by those present. This is hardly surprising, because the minutes of the meeting, which were later obtained through an RTI petition, did not adequately reflect the opposition expressed at the meeting (DC and DEE 2007). To all those present at the hearing, the collusion between the administrative authorities and NPCIL was obvious (Bidwai and Ramana 2007, 10).

The task of evaluating the project and recommending whether to issue environmental clearance rests with the Expert Appraisal Committee (EAC) (see Appendix 3). The EAC has to scrutinize the finalized EIA, the outcomes of the public consultation, the public hearing proceedings and other relevant documents. On 31 August 2007, the EAC met for the first time to evaluate the application for the Koodankulam expansion proposal. Besides the members of the EAC, there were representatives of NPCIL.

According to the minutes of the meeting, the EAC was presented only with NPCIL's response to two written representations—from the Kalpavriksh Environmental Action Group and from the National Alliance of People's Movements (NAPM) (MoEF 2007). Evidently, it was not shown any other submissions, including mine. Nor did the EAC invite members of Kalpavriksh or NAPM to provide a counter response to NPCIL. Many of the EAC's members were drawn from organizations that have links with the Department of Atomic Energy, and those affiliated with the Defence Research and Development Organisation, the Indira Gandhi Centre for Atomic Research and Indian Rare Earths. Not surprisingly, they recommended that the MoEF issue an environmental clearance for the project.

The clearances offered to the Koodankulam reactors are a reflection of the state of environmental governance in the country, especially where it applies to nuclear power plants (Rao and Ramana 2008). Those in authority have not been duly diligent in ensuring that the environment is safeguarded and have been disrespectful of democratic norms. In part, this sorry state of environmental governance when it comes to nuclear facilities has forced people to protest rather than use other means of registering their views.

Thus it was that even in the years after the 2007 public hearing, PMANE and other local groups continued to organize hunger strikes, rallies, and meetings with local government authorities (Roshen 2012). Things heated up after Fukushima (Ramana 2012). Images of the accidents and the multiple reactors blowing up were seen on television screens around the world, including the area around Koodankulam. These provoked strong reactions among the local inhabitants, who could suddenly see concrete evidence of what PMANE had been warning about. NPCIL, on the other hand, went on with their construction and no apparent change of plans. As the first of the Koodankulam reactors was being prepared for commissioning, the locals became increasingly apprehensive.

The last straw, to use a cliché, was during the trial run in August 2011 when dummy fuel was loaded into the reactor. Reportedly, there 'was almost no prior warning given and the local people were caught unawares by what they describe as an unearthly howling sound which continued without respite for the duration of the trial run. This created a renewed sense of panic and near terror among them, made worse by a newspaper warning (subsequently withdrawn) asking people to run in a direction away from the plant with eyes and face covered in case of any symptoms of discomfort and reaction!' (Ramdas and Ramdas 2011, 21).

As one of the many forms of expressing their opposition, people from villages near Koodankulam undertook a relay fast, with volunteers from each village staying without food for a day at a time. By December, the protests had reached such a level of intensity that NPCIL was forced to delay starting operations at the plant. A senior NPCIL executive was quoted in the *Wall Street Journal* saying: 'The protests are continuing and we are just able to do bare minimum maintenance work.' (R. Sharma 2011).

Tamil Nadu Chief Minister Jayalalithaa, who had supported the project, changed her stance and in October 2011, speaking at an election campaign rally for local polls, she declared that the 'Tamil Nadu government will certainly act respecting the local peoples' sentiments. I will be one among you in the issue' (PTI 2011c). But, in March 2012, owing to various political considerations, Jayalalithaa effected a volte-face (*India Today* 2012), coming out in favour of the project and letting loose a round of severe repressions against the local opposition groups and individuals associated with the protests against the plants (Kaur 2012).

Despite this repression, PMANE and a large fraction of the locals continued their opposition. In September 2012, following the announcement that the first of the reactors was going to be loaded with uranium fuel, the locals stepped up their opposition, finding numerous creative ways to demonstrate to the world at large that they did not want this reactor commissioned. Elsewhere in the country, sympathetic groups and individuals did what they could—holding rallies, issuing statements, writing articles and public letters, and engaging in public interest litigation at the Tamil Nadu High Court and the Supreme Court. The Supreme Court even made it clear that it could stop the commissioning of the Koodankulam nuclear power plant if it found that the mandatory safety requirements for it have not been put in place.

None of this was to any avail. The government response was to deploy even greater numbers of police, who used violent force, including shooting down one unarmed protester, and NPCIL continued to get the Koodankulam reactors ready for commissioning. In October 2012, the first of the Koodankulam reactors was loaded with fuel and was expected to go critical shortly. This assault on democracy notwithstanding, the protest movement against the Koodankulam reactors will certainly have implications for India’s nuclear plans.

LOOKING AHEAD

For the better part of a decade, the Koodankulam reactors seemed like a unique proposition. For its own reasons, Russia was prepared to go against the rules of the Nuclear Suppliers Group or, more precisely, to use a loophole in its rules, to supply two VVER-1000s. Other countries, like France, were eager to sell nuclear reactors but unwilling to go against the NSG, of which they were a part. Even Russia could not go against NSG, against the US in particular, to sell another set of reactors. But, with the NSG making an exception for India in September 2008 and allowing it to import nuclear equipment, this situation had changed. Suddenly, there were numerous nuclear vendors ready to sell reactors and other previously proscribed equipment to India.

The DAE, for its part, promised to buy lots of reactors. The WikiLeaks cables, for example, revealed that DAE Secretary Anil Kakodkar told both GE and Westinghouse separately that 'there was place for everybody'.[48] Subsequently, the Nuclear Power Corporation of India shortlisted four major reactor manufacturers—Rosatom, Areva, Westinghouse and General Electric—and announced plans to set up clusters of reactors obtained from these vendors. The preferred sites were to be on the coast to make it easy to transport equipment and fuel.[49]

The site that seems to be first in line is Jaitapur in Ratnagiri district, south of Mumbai. Jaitapur was first named as a potential 'site under consideration to house six 500-MW nuclear units' in 1990 (NEI 1990, 10). But with the collapse of the plans to achieve 10,000 MW by 2000, Jaitapur was left aside till the US–India nuclear deal. Then, as part of the negotiations, NPCIL offered the Jaitapur site to the French Areva company, a fact revealed by the WikiLeaks cables. In addition to these imported reactors, the DAE plans to construct 700-MW PHWRs at non-coastal, interior sites, including Bhimpur in Madhya Pradesh and Kumharia in Haryana (Agrawal 2007; M. Bhardwaj 2008).

The reactions from different states have been mixed. Many state governments have been quick to offer sites, in part because the huge financial costs of constructing the facility are borne by the Central government while they get some share of the electricity. Among them are Haryana and Gujarat (ENS 2007; R. Shah 2008). In contrast, the chief minister of Punjab ruled out setting up a nuclear reactor in Punjab, because the state was densely populated and could not afford the risk of nuclear contamination from reactor accidents (Ahuja 2006).

The West Bengal chief minister initially stated, in November 2006, that the state 'urgently' needs a nuclear reactor in Haripur (*Telegraph* 2006). By 2007, the chief minister seemed to have lost some of his enthusiasm in the face of fierce opposition and stated publicly: 'I have not yet decided on setting up a nuclear power plant as there is divided opinion on it' (PTI 2007b). Orissa has been somewhat less enthusiastic. In the case of the Pati-Sonapur, the state energy minister pointed to a 'variety of issues involved like number of villages to be evacuated as it is a thickly populated area, as also possible health hazards' (Mohapatra 2007).

Where there has been uniformity, it is in the reaction of the local people—in every case, there has been strong, often overwhelming, opposition.

People living around the proposed Jaitapur plant, barring a handful of exceptions, have refused compensation for land and jobs at the project (*Hindu* 2010b). Some have mounted legal challenges (*Hindu* 2010b). At a public hearing to consider the EIA as regards the proposed reactors, opinion among the local participants was unanimous that the reactors should not be built.

In August 2010, even before the environmental clearance had been approved, NPCIL started conducting pre-project activities such as taking soil samples. Inhabitants of Madban village, the closest to the reactor site, were enraged and attacked those taking the samples (*Hindu* 2010c). The Fukushima nuclear accidents of March 2011 led to many locals joining the protest against the Jaitapur project (Bajaj 2011). On 18 April 2011, matters came to a head and hundreds of protesters at Jaitapur were met with police fire; one protestor was killed, leading to the opposition parties forcing adjournment of the Maharashtra state assembly (AFP 2011). Demonstrating a singular callousness both to this opposition and the symbolism associated with the date, the Central government decided to go ahead with the project on 26 April 2011—the 25th anniversary of the accident at Chernobyl (Dhar 2011).

As one strand of opposition, the Konkan Bachao Samiti, an environmental group, has critically analysed the EIA, both the report and the process. In a meeting with Minister of Environment and Forests Jairam Ramesh, Samiti members argued that the EIA prepared by NEERI in Nagpur was ‘unsatisfactory’ because it had not examined the ‘short-term and long-term hazards of nuclear waste generated by the project’ (*Hindu* 2010a). When NPCIL and NEERI members tried to answer the questions, it became apparent that, in the EIA, they had indeed ducked the question of what to do with the spent fuel. There were plans to reprocess the spent fuel eventually, but the environmental impact had not been considered in the EIA report. Also, NEERI admitted that its assertion in the EIA report that ‘solid radioactive waste disposal with effective disposal mechanism will not have any adverse impact on the land and water components of the environment’ was entirely based on the submission by NPCIL to NEERI (Pednekar 2010). All these suggest, yet again, that the EIA process for the proposed reactors at Jaitapur has been extremely lackadaisical and incomplete.

One major concern at Jaitapur is the impact of the reactor on the livelihood of the local inhabitants. The area surrounding the reactor is fertile and there is a large fishing community in the vicinity. Farmers grow a variety of crops, including cashew nuts and mangoes, especially the famous Alphonso variety. The second problem is that it is in a seismic zone IV area and has suffered numerous shocks in the last few decades.[50] In November 2011, two renowned seismologists published a scientific paper based on an extensive examination of the historical record and concluded that a severe earthquake, such as the ones that struck Latur and Koyna, ‘although unlikely … could occur within the lifetime of the nuclear power plant’ in the close vicinity of Jaitapur (Bilham and Gaur 2011, 1275).

At Haripur, again, locals protested and prevented the DAE’s site selection committee from visiting the chosen site. ‘We were unable to visit the site because of agitation by local people,’ a member of the committee told the press (PTI 2006a). The opposition was due to the local people’s concern that they ‘would be dispossessed of their land, their ancestral homestead and their livelihood related to agriculture, sea fishing and sea fish processing’ (Dutta 2007).[51]

Presumably as a way of reducing local opposition, in May 2010, AEC Chairman Srikumar Banerjee said, ‘We have decided to reduce the exclusion or buffer zone from 1.6 km to 1 km at Haripur as we have safer technology at hand’ (R. Bose 2010).[52] The opposition did not diminish and in July 2010, Banerjee could only say that if the nuclear power project did not come up in West Bengal, ‘there will be no impact as there are several other sites on the coastal belt including Orissa and Andhra Pradesh’ (PTI 2010b). In August 2010, newspapers reported that Russia had decided against the Haripur site because of local opposition (Parashar 2010).

In 2011, following the election of Mamta Banerjee as chief minister, the West Bengal government has ruled out the Haripur project (PTI 2011e). The Central government continued to be hopeful and, in a written reply in the Lok Sabha in August 2012 by V. Narayanasamy of the Prime Minister’s Office, listed six 1000-MW reactors as ‘planned to be taken up in the XIII

Five Year Plan and beyond' to be set up with Russian cooperation at Haripur (Narayanasamy 2012a).

There have been similar protests at all the other sites identified for the proposed construction of reactors. As described earlier, such opposition has been witnessed since the 1980s, at Narora, Kakrapar, Kaiga, Bhoothathankettu, Peringome and Koodankulam. This has been the case at uranium-mining sites since the turn of the century, as described in the following chapter.

In addition to the obvious concern about releases of radiation and catastrophic nuclear accidents, opposition to nuclear facilities is also due to their impact on lives and livelihoods. In the case of reactors, for example, the reactor's requirements for cooling water and land compete with the needs of farmers. On inland sites, the water problem could be even more acute.[53] Similar factors also drive opposition to large hydroelectric dams, thermal power plants and automobile factories.[54]

Because of intensifying conflicts over natural resources, opposition to new nuclear sites will get intensified in the future. Water scarcity, for example, is becoming more severe by the year. The consulting company McKinsey projects that the demand for water in India will outstrip supply by 50 per cent by 2030 (2030 Water Resources Group 2009, 15). Another factor that might become more difficult in the future is the ability to offer land as compensation to those displaced. Even up to now, the treatment meted out to those dispossessed by nuclear facilities already commissioned has been less than satisfactory. In 2003, the Lok Sabha Standing Committee on Energy noted: 'A number of assurances are given to land oustees by the Department of Atomic Energy and State Governments at the time of acquisition of land for the purpose of setting up of Nuclear Power Stations. These assurances are seldom honoured. The land oustees run from pillar to post to have these assurances fulfilled' (Standing Committee on Energy 2003a, para 16).

Such a trend of opposition to nuclear facilities will heighten the contradiction between a democratic society—which requires that the rights of all be respected and which requires that the state maintain its legitimacy in the eyes of the public—and the demands of a successful nuclear industry—which requires that its immensely expensive projects be speedily executed, and opposition be ignored or silenced by force. How this contradiction is resolved will determine the future not only of nuclear power in India but also of democracy itself.

3

Uranium

> *From 1947 until the early 1960's, two Federal agencies* [in the United States] *struggled in secret over the fate of thousands of men who were being exposed to hazardous levels of radiation while mining uranium … The Atomic Energy Commission prevailed in the battle over mine safety with the Public Health Service. The result has been a widening trail of deaths and disabilities from lung cancer across Arizona, Colorado, New Mexico and Utah … Across the four-state region, once-robust mining towns … are becoming ghost towns inhabited by widows and aging men who live with one lung and the daily worry of developing cancer in the other.*
>
> —Keith Schneider (1990), *The New York Times*

Uranium is the basic material that enables the generation of nuclear energy. For decades, the DAE's Atomic Mineral Directorate for Exploration and Research (AMD) has been searching all over India for deposits of the mineral, finding substantial quantities of it in states ranging from Meghalaya to Jharkhand to Andhra Pradesh. However, as with reactor projects, local populations have opposed mining in most of these areas and several proposed projects have been long delayed. These delays, when coupled with poor planning by the DAE, have led to shortages of uranium which, by around 2006, led to reactors having to be run at lower power levels or even shut down. In the future, as NPCIL begins to import larger quantities of uranium, the mining of uranium within the country will become less important to the future of nuclear power in India. However, uranium cannot be imported for military activities. Therefore, to fuel the many reactors which the DAE has included in its list of strategic reactors, and for the uranium enrichment programme, uranium mining within the country will continue.[1]

HISTORY

On 26 April 1948, Homi Bhabha, the founder of India's nuclear programme, wrote to Nehru proposing to start an extensive search for uranium. Surveying for atomic minerals was one of the immediate tasks of the newly formed Atomic Energy Commission. Since there was no evidence of large deposits of uranium in India, Bhabha felt it best to warn Nehru that the 'geological surveys would take at least two years … it is possible that their result may be negative' (Parthasarathy 2006).

The urgency to find uranium and other atomic materials was twofold. The first and obvious one was that, without adequate quantities of such materials, the AEC could not make a case for a large atomic energy programme based on domestically available resources. The less obvious one was that the AEC was trying to use these ores as tradable commodities to strike deals with nuclear establishments in other countries, notably the United States of America.[2]

Cold War politics interfered in many ways. In 1953, for example, India exported a small shipment of thorium nitrate to 'Communist China'. Just two years earlier, the United States had passed the Mutual Defense Assistance Control Act that stated that all US 'financial, economic, or military aid to another country automatically be terminated if that country were found to be trading embargoed items to the U.S.S.R., its satellites, and Communist China' (Helmreich 1986, 231). Among the list of embargoed items were uranium and thorium. The discovery of the shipment promised to blow up into a diplomatic embarrassment. Eventually, this particular shipment was allowed to go through but the United States had to agree to purchase India's entire output of thorium nitrate, a material not required by the US Atomic Energy Commission—as it already had plentiful supplies with no effective demand—and at a rate substantially higher than the global market rate (Helmreich 1986, 232–35). These purchases were to go on for a period of eighteen months or until 230 tonnes of thorium nitrate were delivered.

The AEC's search was led by the geological adviser to the government, D.N. Wadia, who had done pioneering work on the geological history of north-western Himalayas (Koppiker 1995, 35; V.C. Thakur 2003, 66–73). The initial team consisted of seventeen geoscientists who were grouped under the Rare Minerals Survey Unit under the then ministry of natural resources and scientific research; the unit was subsequently renamed Raw Materials Division (RMD) and brought under the Atomic Energy Commission in 1950.

The first couple of years of hunting for uranium were not particularly successful. From April 1950 onwards, the government issued a series of notifications and press notes offering rewards for the discovery of atomic minerals, especially uranium and beryl ore.[3] The rewards were considerable. In the first notification, for example, the government offered up to Rs 10,000, a significant sum in those days, for any deposit that was more than fifty miles (80 km) from any other deposit known to the AEC, and that was found to be capable of producing 50 tonnes of uranium oxide ore with an ore grade of 0.4 per cent or more (Bhatnagar 1950; DAE 1958, 20–21). The ore grade is essentially the concentration of the material of interest in the ore; the higher the ore grade, the greater the amount of uranium that can be extracted from a given quantity of ore. To stimulate the discovery and the exploitation of deposits of uranium ore, the government also offered to pay a grant for mine development to any applicant who produced 20 tonnes or more of ore from any mining lease or concession not previously worked for uranium ore. The AEC offered to do radioactive tests of samples sent in and, if warranted, conduct further chemical and field tests.

A similar announcement in July 1950 declared that the government had decided ‘to purchase all stocks of uranium available with dealers or mine-owners’ (DAE 1958, 28). The price was to be based on the uranium content and was set at a ‘minimum rate of Rs 9 per pound of uranium oxide’ and the price was guaranteed for five years. The announcement also warned that, under the Atomic Energy Act of 1948, the government could compulsorily acquire uranium, since it was a ‘prescribed’ mineral, and it would be ‘advantageous for dealers and mine-owners or persons possessing stocks of uranium to sell their stocks … at an early date’ (DAE 1958, 29). The government also undertook similar measures to procure beryl and lithium ore.

The announcements seem to have spurred activity and soon there were many prospectors; some even called on the AEC to publish a ‘handbook detailing the nature of occurrence of uranium in India and the techniques of prospecting' (N.R. Srinivasan 1951, 9).[4] It is not clear whether the AEC did comply with that call. Despite public enthusiasm, it appears that the prospecting did not produce too much uranium that met with the criteria set down by the AEC, in particular, that the ore grade be higher than 0.4 per cent. After some years, 'on further consideration', the government 'decided to give smaller rewards for discovery of deposits of Uranium bearing rocks which fail to fulfil the above conditions'—rewards ranging from Rs 100 to Rs 1000, provided that the deposits were fairly extensive and not small, isolated, local pockets of uranium minerals (RMD 1954; DAE 1958, 25). In further announcements, the AEC also specified in what mineralogical forms uranium is found in nature, the colours of typical uranium-bearing minerals, and simple tests to detect uranium.

Though it is not clear whether any independent prospectors did succeed in finding uranium, the AEC's surveys bore some success. In January 1951, the minister for natural resources and scientific research announced the discovery of two uranium belts in eastern and central India (*Engineering and Mining Journal* 1951, 144; Keiser 1954, 1313). This was reported on the front page of the *Statesman* in Delhi, which went on to note that 'the precise location … remains a well-preserved secret' (Abraham 1998, 106). This was where the Jaduguda mines were eventually set up. Among the other locations identified as having anomalously high radioactivity levels were Bhatin, Narwapahar, Turamdih and Bagjata (Bhasin 1995, 307). The same year, the Directorate of Mines and Geology, Government of Rajasthan, announced that uranium had been found in the Aravalli hills near Udaipur (Keiser 1954, 1313–14).

Neither of these locations should have come as a surprise. One clue that geologists worked with was that, in several countries, uranium was known to be associated with copper. Both Bihar and Rajasthan were known to have copper deposits. Indeed, the earliest reference to a uranium mineral in India was in an 1860 German publication to copper uranite in the Singhbhum area (Brown and Dey 1975, 430). A little over a decade prior to the commencement of the AEC's prospecting for uranium, the presence of uranium at Mosaboni had been reported by a British prospector in 1937 (Koppiker 1995, 35). This was confirmed in 1950.

Though uranium deposits were identified in Jaduguda in the early 1950s, figuring out how to recover the uranium from other minerals proved difficult. Samples of ore were sent to laboratories in the United States, the United Kingdom and Australia, and foreign experts were brought in at high expense (Koppiker 1995, 36). When the AEC decided to open an underground mine in Jaduguda in 1959, it brought in a French mining expert to help start the activity. The following year, it was decided to set up a uranium mill near the mine. The sinking of the first shaft—the vertical tunnel through which the underground part of the mine is accessed from the surface—started in 1964 and the mine became operational in 1967.

The discovery of this first couple of deposits was not enough for the AEC, which envisaged a large-scale nuclear power programme requiring vast quantities of uranium. The search continued and potential sources of uranium in other states, including Bihar, Madhya Pradesh, Uttar Pradesh, Himachal Pradesh, Meghalaya and Andhra Pradesh, were identified (Bhasin 1998, 18). Some of these locations were at existing mines. In 1956, for example, the DAE tested a specimen from the Bhunas mine in Rajasthan which had been developed to produce ruby mica, and it was found to contain uranium (Udas 1958, 709).

Simultaneously with the efforts to discover uranium ore, a chemistry laboratory was set up in December 1949 to develop techniques to estimate the quantities of uranium. The laboratory was set up at Bhabha's ancestral home on Pedder Road in a posh locality in Bombay (Koppiker 1995, 35).[5] Soon, acid fumes from the laboratory became unbearable to the neighbours and in July 1954 it had to be moved out. The new location was an abandoned godown which belonged to Bombay Dyeing Co., in Prabhadevi, a middle-class neighbourhood of the city. Locals had no idea what was going on and the building began to be called 'automatic factory' (Koppiker 1995, 35). The laboratory was finally shifted in stages to the Bhabha Atomic Research Centre campus in Trombay in 1967.

ESTIMATES

Speaking at the First Conference on the Peaceful Uses of Atomic Energy held in Geneva in 1955, Bhabha announced that India had 'known deposits of uranium ore containing more than 0.1 per cent uranium have a total uranium content of roughly 15,000 tonnes' (Bhabha 1955, 104). These figures were to go up. By 1958, the DAE had announced that workable uranium deposits were expected to yield some 30,000 tonnes (*Nuclear Engineering* 1958, 422). That amount would suffice to fuel about 5000 MW of heavy water reactors for forty years. For comparison, the total installed generating capacity in the country, including coal, oil and hydropower plants, in 1960, was 4653 MW (Surrey 1988, 366).

The early estimates are somewhat vague and do not differentiate between diverse resource categories. Globally, the standard source of information on uranium resources is the annual Red Book produced by the International Atomic Energy Agency and Nuclear Energy Agency (NEA). This has been published since the mid-1960s and is based on information provided by various countries to the IAEA, as well as on the IAEA's own estimates.

The Red Book categorizes uranium resources into conventional or unconventional resources: 'Conventional resources are those that have an established history of production, where uranium is a primary product, a co-product, or an important by-product (for example, from the mining of copper and gold). Very low grade resources or those from which uranium is only recoverable as a minor by-product are considered unconventional resources' (NEA 2002b, 13–15). All other sources of uranium are also considered unconventional resources.

The Red Book further divides conventional resources into multiple categories based on how confident one can be of the resource estimates. The most important of these are Reasonably Assured Resources (RAR) and Inferred Resources (IR) previously known as Estimated Additional Resources (EAR). RAR refers to uranium resources that have a high assurance of existence because they occur in known mineral deposits. Because their grade is known, it is usually possible to estimate the quantities that may be recovered from that deposit within some specific production cost ranges, using currently proven mining and processing technology. IR refers to uranium deposits that are not included in the RAR category, and are inferred to occur on the basis of direct geological evidence. In these, though, the knowledge about the characteristics of the deposits is usually too inadequate to provide the kind of information that is required to categorize the resource as RAR. Less reliance can be placed on the estimates in this category than on those for RAR. There are also other unconventional resources, such as phosphate deposits that are typically not included in the Red Book. Table 3.1 lists the estimates for India of some of the recent Red Books.

TABLE 3.1. ESTIMATES FOR INDIA'S URANIUM RESOURCES AS PER VARIOUS RED BOOKS

Report	**Reasonably Assured Resources (RAR)(t)**	**Estimated Additional (EAR)/Inferred Resources (IR)(t)**
1993 Red Book	50,680	15,680
1999 Red Book	52,745	25,202
2001 Red Book	54,470	23,560
2003 Red Book	54,636	25,245
2007 Red Book	61,100	30,000
2009 Red Book	72,800	33,100
2011 Red Book	102,600	37,200

Sources: NEA 1994, 159; 2000, 175; 2002b, 184; 2004, 146; 2008b, 207; 2010b, 224–25; 2012, 249.

The 2011 Red Book—the most recent at the time of writing this—states that the known conventional resources amount to 139,800 tonnes of uranium (NEA 2012, 248). This is considerably higher than the estimates of the 1950s. The 2011 Red Book also reported an additional 80,600 tonnes in unconventional resource categories on which less confidence can be placed, and reports that identified conventional resources can support 10,000 to 15,000 MW of heavy water reactors over a lifetime of forty years at 80 per cent capacity factor (NEA 2012, 253).[6]

Notwithstanding the certainty with which the DAE has frequently made statements about how much uranium is available in India, the actual extent of uranium resources is by no means fixed. It depends on the extent of mineral exploration and exploitation of different kinds of deposits. As shown in Table 3.1, uranium resource estimates have been steadily increasing as a function of time, especially in the more reliable RAR category. Based on trends observed in other minerals and their availability, analysts suggest that 'the Red Book data should be viewed as a conservative lower bound on supply in the short term and a reasonable point of departure for extrapolation of longer-term supply estimates' (Schneider and Sailor 2008, 386). Further, the Red Book estimates are for uranium available at a certain cost; at higher costs, more uranium from ores of poorer quality will be available.

Though, on the one hand, the DAE has been bemoaning the lack of uranium and investing in reprocessing and fast breeder reactors, it has also been engaged in a systematic effort to increase uranium production. One technological effort has been to recover uranium from secondary sources, such as phosphates and monazites. The most important secondary resources of uranium are uraniferrous phosphate rocks that are imported from various countries in large quantities by Indian fertilizer companies (Mukherjee and Singh 2003, IT-7/4). In the DAE's judgement, there is a substantial potential for recovery of uranium from the phosphates, which it estimates at about 1000 tonnes/year (H. Singh 1999, 22). The second strand has been accelerating uranium exploration. The DAE, through the Atomic Minerals Directorate, has been involved in extensive uranium exploration activities, spending over 2.5 billion rupees in 2010 on increasing uranium resource estimates (NEA 2012, 254).

LOCATIONS AND QUALITY

Uranium has been found in many places around India in different kinds of deposits. However, practically all of the deposits that have been found so far are of poor quality, that is, low ore grade. About 38 per cent of the uranium reserves in the RAR and IR categories are in what are called vein type deposits (NEA 2012, 249). Note that the relative fractions of different types of deposits change continuously as newer deposits are discovered and older ones are used up.

In vein deposits, the major part of the deposit is found in fractures in the underlying rock. The largest vein deposits in India are those in the Singhbhum belt in Jharkhand. The thickness of the vein—a term used by geologists—or lode, the nearly equivalent term used by miners—can be variable. In some countries, like the Czech Republic, Germany and Congo, these are thick and massive. In India, these are typically thinner. The Jaduguda mine, for example, has two ore bodies, the Footwall Lode (FWL) and the Hanging Wall Lode (HWL), whose average width is about 3–4 m although, in certain places, they are as thick as 20–25 m (Bhasin 1995, 308).

The highest grade ore located in the Jaduguda area averages only 0.067 per cent of uranium oxide (U_3O_8), and that constitutes only about 6 per cent of the total estimates for the region (Sarkar 1984, 199). This was in the early years; over time, the better quality ores have been exploited. The bulk of the reserve, estimated at around 80 per cent of the total, is in the form of even lower-grade ores containing 0.02 to 0.049 per cent of uranium oxide (U_3O_8). In comparison, the average ore grade of uranium mined around the world is 0.15 per cent, with the highest quality ore containing over 20 per cent uranium oxide. The DAE seems to have decided to mine even low-grade ores regardless of the cost. Indeed, the AMD argues that in 'developing countries like India where there is a high rate of unemployment, especially in the unskilled to semi-skilled category, mining of low grade deposits is a desirable option' (Chaki, Purohit, and Mamallan 2011, 157). However, mining low-grade ores will lead to increased environmental impact because the amount of ore which would have to be mined to obtain each unit of uranium is so huge.

Another important source of uranium is called a strata-bound deposit, where the mineral is found within two layers of rock that are different in character. At Tummalapalle in Kadapa district, the uranium is found in a plane in dolostone, a sedimentary carbonate rock somewhat similar to limestone, that extends over 160 km. The Tummalapalle deposit is estimated to contain over 15,000 tonnes of uranium oxide (U_3O_8) with an ore grade of 0.042 per cent (Sinha and Saxena 2003). The problem with this deposit has been that the specific form in which the uranium is found does not allow easy leaching using alkalis. Nor does the small size of the uranium mineral form (pitchblende) allow for cheap extraction. Indeed, in the late 1990s, the Atomic Minerals Directorate had decided that 'the cost of extraction of uranium from this deposit is beyond the [*sic*] present day economics' (D.C. Banerjee 2005, 85).

The next leading kind of uranium resource in India is the unconformity type; such deposits constitute about 12.3 per cent on the RAR and IR categories (NEA 2012, 249). Some of the highest quality and economically most attractive deposits around the world, especially in Canada and Australia, are of this type. The first unconformity-related uranium deposit in India was discovered only in the early 1990s in the Kadapa (formerly Cuddapah) basin in Andhra Pradesh, in Lambapur-Peddagattu in Nalgonda district, and in Koppunuru in Guntur district (Sinha and Saxena 2003). However, these deposits, unlike those in Canada and Australia, are not of very high quality.

Uranium is also found in sandstone types, which contain about 11.8 per cent of the RAR and IR categories (NEA 2012, 249). Sandstone deposits are typically considered more economically attractive than vein deposits. The largest sandstone uranium deposits so far found in India are along the southern fringe of the Meghalaya Plateau, in Domiasiat, Wahkyn and Umthongkut (Srivastava et al. 2008, 1573). They occur amidst sandstone at a shallow depth below the surface. These deposits have an average grade of about 0.10 per cent of uranium oxide (U_3O_8).

Other locations in India that have uranium occurrences are the Aravalli belt in Rajasthan, as mentioned earlier; the Bhima basin in Karnataka; and the Vindhya basin in central India, especially in the Son valley in Uttar Pradesh. Many other locations are being intensively investigated.

MINING AND MILLING CAPABILITIES

Uranium mining is carried out by the Uranium Corporation of India Ltd. (UCIL) which is a Government of India undertaking under the administrative control of the Department of Atomic Energy. UCIL was established in 1967 and started its operations in 1968 at Jaduguda with uranium-ore mining and a processing plant (Gupta 2004, 58).

Mining is carried out in Jaduguda up to a depth of about 900 m. The first stage of the mineshaft was 315 m deep and was constructed between April 1964 and March 1967; the second stage, from 315 m to 640 m, was constructed between February 1971 and December 1977; the third stage, from 640 m to 905 m, was constructed between December 1998 and September 2004 (Sundaram, Krishnan, and Iyengar 1998, 80–83; MoSPI 2005). Construction of the mill in Jaduguda started in 1962 and was completed in 1967.

Jaduguda remained the only uranium mine in the country for nearly two decades. Subsequently, mining of two other deposits at Bhatin and Narwapahar, about 3 and 12 km from Jaduguda respectively, was started in 1986 and 1995 respectively. The ore from these mines is processed in the mill at Jaduguda. A small quantity of uranium, extracted from the tailings produced by the copper plants at Surda, Rakha and Mosaboni, which contain about 0.005–0.009 per cent uranium oxide, is also processed in this mill (Khan et al. 2000, 184).

In 1989, the DAE began establishing a mine and mill in Turamdih, again not far from Jaduguda. At that time, the DAE was still maintaining that it would construct 10,000 MW of reactor capacity by 2000. But, as it became clearer that plans for reactor construction were going way behind schedule, the DAE abandoned the mining and mill project at Turamdih in October 1994, and transferred 165 acres of township land with buildings at Turamdih to the Central Reserve Police Force (CRPF) for Rs 21.22 crore (CAG 2000). The land thus transferred had actually been acquired from poor tribal farmers with minimal compensation under the Land Requisition Act (Dias 2005, 3568).

With the increase in budget following the 1998 nuclear tests, and the DAE's expectations of an increase in nuclear generation capacity, the department started re-examining Turamdih even though one of the reasons for abandoning it earlier had been the very poor quality of its ore. Indeed, the former head of the Geological Survey of India J. Coggin Brown had dismissed Turamdih and Mohuldih as having 'no workable deposits' (Brown and Dey 1975, 439). Nevertheless, in 2002, faced with a potential uranium shortage, the DAE started work on reopening the Turamdih mine (*Nuclear India* 2003, 1). Since most of the work had been completed more than a decade earlier, the mine began operation in 2003.

Around the same time, UCIL quickly moved on three projects: Banduhrang, Bagjata and Mohuldih. There was substantial local resistance to all three projects, mostly on account of UCIL's not compensating those displaced by earlier mines and mills.[7] In the case of Mohuldih, even the Jharkhand State Pollution Control Board (JSPCB) reportedly termed the demands of the locals 'just' and 'genuine'.[8] But UCIL proved stronger and, in June 2007, the Banduhrang uranium mine, the corporation's first open pit unit, began operations. Around the same time, the Turamdih mill was also inaugurated.

Outside of Jharkhand, the Atomic Minerals Directorate began extensive explorations in Meghalaya in the 1980s (NEA 1994, 157). In 1990, AMD confirmed the presence of a rich vein of uranium. Later estimates suggest that the state has 9.22 million tonnes of ore. Given the quality of ore expected, that is estimated to yield about 9500 tonnes of uranium (NENA 2006). Soon after AMD's announcement in 1990, there was talk of setting up a mine and mill during the eighth plan period (1992–97) with a capacity of 250 tonnes/year (ToI 1993).

These plans did not materialize. The 2001 Red Book had 2008 as the planned start-up date for mining in the region (NEA 2002b, 187), but the 2003 Red Book did not even mention Meghalaya (NEA 2004, 148–49). According to S.K. Malhotra of the DAE, 'UCIL [has been] trying its best to start mining since 1998' in Meghalaya (*Assam Tribune* 2006). One problem, that UCIL does not mention publicly but has admitted in informal and non-attributable conversations, is that its personnel did not want to move from the Jaduguda area—where they have an established base—to Meghalaya and such locations where they are clearly unwanted and resented. Nevertheless, in June 2006, Ramendra Gupta of UCIL announced that the 'road to the mining area had already been constructed' and that mining would start 'next year' pending a clearance from the ministry of environment and forests (PTI 2006b). However, as of June 2010, the road had not yet been completed.

The clearance came in December 2007 (*Assam Tribune* 2007). But then, during the elections which followed a couple of months later, the coalition of parties that came to power had promised the people of the state that mining would not start without their concurrence (Karmakar 2008). In the meantime, UCIL started eyeing another site in Meghalaya, this time in the Balpakram National Park. But in May 2010, the proposal was rejected by the ministry of environment and forests. Despite many twists and turns, mining hasn't commenced in Meghalaya as of August 2012.

The troubles in Meghalaya forced UCIL to turn its attention to another state: Andhra Pradesh. In 2002, it started planning to undertake open-pit and underground mining at the Lambapur-Peddagattu deposit; operations were expected to commence in 2006 (NEA 2004, 148–49). The site had been identified in the 1990s, and AMD had been handed over a section of the Nagarjuna Sagar-Srisailam Tiger Reserve for uranium exploration. The tiger reserve used to hold over ninety tigers, but the 1995 census recorded only thirty-four. The beleaguered status of the tigers did not deter AMD, whose officials reportedly claimed that there was 'no wildlife activity in the Sanctuary at all'; a newspaper quoted the director of AMD as saying 'leave alone tigers, we did not see even jackals' (TLN 1998). In 2003, State Minister for Mines and Geology Uma Madhava Reddy announced in the Legislative Assembly that UCIL's applications for a mining lease covering the Lambapur-Peddagattu area and an ore-processing plant were being processed (Subbarao 2003).

These plans ran into a different set of problems: the mining site was next to the Nagarjuna Sagar Reservoir, the source of drinking water for Hyderabad; and the initially proposed site for the processing plant was less than 5 km from the Akkampally Reservoir (Anand and Gokhale 2003). Seeking to achieve political mileage from this fact, the late Y.S. Rajasekhara Reddy, then the head of the opposition Congress party and chief-minister-in-the-making, came out against the project, terming it ‘frightening’ (Y.S.R. Reddy 2003). Another source of opposition was the Naxalite group People’s War which set fire to drilling machines, generators, trucks, and a jeep belonging to the Atomic Mineral Directorate as part of its protests against the proposed uranium project (*Hindu* 2003).

UCIL then proposed to move the processing work to Seripally, about 50 km away from the mine, further away from the water bodies. This time, things moved faster. The Corporation held a public hearing in March 2005, where fifty-seven out of sixty speakers opposed the uranium mill (*Hindu* 2005b). Rajasekhara Reddy, who had by then become the chief minister, turned around and maintained that the state government did not have any stake in the approval, and it was for the Central government (also led by the Congress) to decide (Dubey 2005). MoEF issued an environmental clearance for the mining project in December 2005 (HT 2005).

The clearance was challenged by Capt. J. Rama Rao, a retired naval officer, at the National Environment Appellate Authority (NEAA). The key function of the NEAA, which was set up under the National Environmental Appellate Authority Act 1997, was to hear appeals against environmental clearances accorded to industrial and developmental projects. (Since then, the NEAA has been replaced by the National Green Tribunal.) The NEAA dismissed the case in November 2008, claiming that ‘while pursuing the national goal in the power sector, UCIL has provided for adequate safeguards and safety measures against any possible eventualities in this project’. This, again, was not surprising. In February 2009, the Delhi High Court noted that the National Environment Appellate Authority, in its eleven years of existence, had dismissed all appeals filed. Therefore, the Court observed, ‘it is at present neither an effective nor an independent mechanism for redressing the grievance of the public in relation to the environment clearances granted by State or Central Government’ (P. Ghosh 2009).

The second mining site in Andhra Pradesh that UCIL has been pursuing is Tummalapale in Kadapa district. Though the deposit was discovered in 1986, even as late as 2004 it was not being seriously considered for mining (Awati and Grover 2004, 13). The first indications of the project came in February 2006 during a television interview of Rajasekhara Reddy, who announced that the Tummalapale deposit, which happened to be located in his own constituency, ‘may be’ the first of the Andhra uranium-mining projects (D’Souza and Sudhir 2006). Things moved fast after that and in September

2006 a public hearing was conducted, where many who had gathered to oppose the project were physically attacked by the police (*Hindu* 2006a). In August 2007, the Cabinet Committee on Economic Affairs (CCEA) gave its approval to the project, which has been estimated to cost Rs 1106.29 crore (*Hindu* 2007a). In April 2012, the Tummalapalle mine and associated mill were commissioned (Mail Today Bureau 2012).

Neighbouring Karnataka's government appears to be enthusiastic about hosting a uranium mine. In June 2012, the state government and UCIL signed a memorandum of understanding to set up a mine and associated processing plant in Gogi (PTI 2012b). According to the MoU, the Karnataka government would help UCIL to obtain permissions, registrations, approvals and clearances from the concerned departments as per the existing policies and rules and regulations of the state government. Residents of Gogi village and surrounding areas, along with local legislators, have strongly opposed uranium mining (*Hindu* 2011). They have had bitter altercations with the authorities at various forums, including at a workshop held in June 2012 (*Hindu* 2012).

The eight operating mines as of August 2012 were Jaduguda, Bhatin, Narwapahar, Bagjata, Turamdih, Banduhrang, Mohuldih—all in Jharkhand—and Tummalapalle in Andhra Pradesh. All except Banduhrang are underground mines. According to the 2011 Red Book, they had capacities of 650, 150, 1500, 500, 750, 3500, 500 and 3000 tonnes of ore per day respectively. Ore from the first four mines was processed at the Jaduguda mill, which has a capacity of 2500 tonnes/day. Ore from the three other mines in Jharkhand are processed at Turamdih, which has a current capacity of 3000 tonnes/day; the mill is being expanded to process 4500 tonnes/day. The average process recovery at the two mills is said to be 80 per cent (NEA 2012, 251; 2010b, 228). Ore from Tummalapalle is to be processed at the Tummalapalle mill, which has a current capacity of 3000 tonnes/day (NEA 2012, 251; 2010b, 228). Both the mine and the mill at Tummalappalle are being expanded to 4500 tonnes per day.

LOCAL REACTIONS

The general reaction to proposals for uranium mining around the country has been negative. Because it was started before there was widespread awareness about nuclear and other industrial hazards, the Jaduguda area is the only area where uranium mining and milling activities have not been significantly opposed by the local population. By the early 1990s, however, some in the region had started becoming aware that uranium mining was exacting a toll on the health of the local inhabitants (see chapter 8 for more details). The Jharkhandi Organization against Radiation (JOAR) was formed then and it has attempted to increase the public's knowledge of the situation in Jaduguda. In 1999, Shri Prakash made a film titled *Buddha Weeps in Jaduguda*, which documented diseases in the community, including congenital defects in newborns, and sterility in young women, as well as some poor work practices followed by UCIL, such as loading yellow cake in leaking drums. *Jang aur Aman*, the 2002 award-winning documentary by Anand Patwardhan, also showed the many health impacts on workers and the local community from uranium mining and milling.

Issues of land and livelihood have also been cause for opposition. The trouble started in the mid-1980s. There were already two valley-dam types of tailings ponds at Jaduguda, which are 33 and 14 hectares respectively (Khan et al. 2000, 186). Both were nearly full and UCIL wanted to construct a third tailings dam. In 1985, it served notice to the inhabitants of Chatikocha (also spelt Chatijkocha), a tola or hamlet of Bhatin, that their land was needed. Chatikocha was prosperous, with good crops, forest products, and was the seat of famous theatre groups (EPW 2000, 3984). Naturally, the villagers didn't want to be displaced. For nine years nothing happened. In 1994, 'the villagers were directed to appear at the UCIL offices to collect their compensation because their land had been acquired. Most families were deeply offended by the pitiful compensation offered by UCIL and refused the offer, delivering instead a set of demands which were ignored' (Ludlam 2000, 24).

On 27 January 1996, the UCIL management, assisted by the Central Reserve Police Force, the Central Industrial Security Force, the Bihar Police, a set of heavy bulldozers and a high-powered shovel, entered Chatikocha and started razing down the houses without any warning. The houses of over thirty families were levelled together with their fields and crops, their sacred groves and graveyards (Mining Concerns Desk 1996). Soon, the locals, mostly adivasis belonging to the Santhal, Ho and Munda communities, had mobilized a large number of people from nearby villages in support of the people of Chatikocha, and UCIL suddenly found it had an uprising on its hands. It apologized and the demolition was temporarily suspended but it did not rehabilitate the people (EPW 2000, 3984).

The villagers demanded just compensation for their lands and approached the Ranchi Bench of the Bihar High Court in mid-1996 seeking to stop UCIL from destroying their village completely (Ludlam 2000, 24). The court did not rule on the case and instead suggested that the villagers negotiate with UCIL. In the meanwhile, work on the tailings dam was quietly recommenced in February 1997. Many of those displaced have started living in houses adjacent to the tailing pond (Barla 2007). Negotiations with UCIL, in the meanwhile, did result in many people from Chatikocha being given jobs in the mines and mills, after which the opposition died down somewhat.

By the turn of the century, UCIL's efforts to open new mines, and sometimes even to operate existing ones, in the Singhbhum region were being met with protests. Prominent among these was the mine in Mohuldih, which faced violent opposition from local inhabitants. In August 2005, an attempt by the Pollution Control Board of Jharkhand state and UCIL to hold a public hearing to discuss the environmental impact assessment report for the mining project 'was thwarted by the residents of more than a dozen villages around Mohuldih … [who] said they neither needed a hearing nor a uranium mine' (Narain 2005). Yet another attempt in December of that year was also resisted.

Similarly, at the public hearing held in Banduhrang on 25 February 2004, three villages refused to be displaced (Mahapatra and Jayan 2004). Subsequently, in May 2007, local people who had been displaced by UCIL activities in Turamdih came together under the banner of Turamdih Displaced Committee (TDC) and disrupted mining activities at the Banduhrang mine. UCIL had to seek the help of East Singhbhum district administration to continue its operations.

Places farther away from Jaduguda have been even more resistant. As mentioned earlier, opposition to uranium mining and milling was clearly expressed at the public hearings in Andhra. But the best illustration of the widespread nature of opposition to uranium mining is Meghalaya. Outside of the Singhbhum area, Meghalaya is said to have the largest reserves of uranium in India. In 2006, R.M. Sinha, director of the Atomic Minerals Directorate, stated, 'Our main concentration now, after Singhbhum, is on Meghalaya' (Subramanian 2006e).

But Meghalaya proved a problem area from the very beginning. This small state is largely inhabited by indigenous groups like the Khasi, Jaintia, Garo and Mikir who constitute 86 per cent of the state's total population. These indigenous groups and their respective district councils manage the forests and lands, thanks to the sixth Schedule of the Constitution of India (Shimray and Ramana 2007, 15). Of the state's estimated total forest land area of 8514 sq. km, only 993 sq. km is directly under the control of the Forest Department. In other parts of the North East, too, the government controls only a small portion of the total forest land. For the project to go forward, all the required land acquisition 'needs to be ratified by the entire clan or the individual owner'. It has been argued that 'To mine in Meghalaya, DAE will have to change the provision of the VI Schedule of the Constitution' (Dias 2005, 3568).

But these indigenous groups have so far been unwilling to allow uranium mining. In Domiasiat, UCIL has been facing bitter opposition from the local Khasi tribe. One senior UCIL official confessed to the British Broadcasting Corporation: 'Every time we turn up at the uranium mines, the tribes people chase us with bows and arrows and swords … They call us the agents of death and threaten to kill us if we try to mine uranium' (Bhaumik 2003). Protestors routinely portray the issue as being one of the Khasi people versus the 'foreigner' or the 'outside exploiter' (Karlsson 2009, 46).

On 12 June 2007, a public hearing to discuss the environmental impact of the project was held in Nongbah Jynrin, West Khasi Hills. One of the leaders of the opposition, the powerful Khasi Students' Union (KSU), called a 36-hour bandh. Despite the government's efforts to thwart the strike, for example, by directing all government employees to attend office (*Shillong Times* 2007), the bandh was largely successful. For leading the opposition, many of the KSU's members were arrested under the draconian Meghalaya Preventive Detention Act.

Local concerns are many. One is that their livelihood system will be eroded by uranium mining. Yet another related concern has been that a large-scale influx of non-indigenous people into the region will reduce the local Khasis to a minority. And finally there are health and environmental concerns. In the light of how the government and UCIL have dealt with the opposition, one might add disregard of local democracy and human rights to the list of concerns.

Finally, in the 2008 state elections, the winning coalition included one of the parties strongly opposed to uranium mining. In April 2008, Meghalaya Deputy Chief Minister Hoping Stone Lyngdoh declared, 'I will take up the matter before the Cabinet and request our coalition partners not to issue a No Objection Certificate to the Uranium Corporation of India Limited (UCIL) for mining in Meghalaya.' This was one of those rare occasions when popular will and democracy were being reflected in nuclear policy matters.

The DAE's stated goal 'is to achieve self-sufficiency in uranium resources in order to support its presently envisaged natural uranium based nuclear power programme as well as future requirements' (Awati and Grover 2004, 12). Since the programme is ambitious, the uranium requirement has to be correspondingly ambitious. There is, therefore, an extensive exploration programme for uranium in various areas of the country. But the DAE's long-term hope is to move away from uranium and into the so-called closed nuclear fuel cycle, where more of the power will be generated from plutonium, an even more radioactive element.

4

Plutonium

We should not rely for energy supply on a process that produces such a hazardous substance as plutonium unless there is no reasonable alternative.

—The Royal Commission on Environmental Pollution (Flowers 1976)

To most people who have studied the element, what are most important about plutonium are those very properties that might be the source of harm to life: its radioactivity, its toxicity, and its ability to sustain a chain reaction and release explosive energies (that is, its potential for use in nuclear weapons). Thanks to these properties, plutonium has been described as the world's most dangerous element (see, for example, Bernstein 2007). Others have described it as the 'deadly gold of the nuclear age', pointing out that 'like gold, it has wreaked environmental damage and endangered the lives of people around the globe … Just as the quest for gold left in its wake many human tragedies, the quest for plutonium has created many tragedies, some of which we do not know how to address to this very day' (Hu, Makhijani, and Yih 1992, 1–3). Many people have, therefore, called for a cessation of the production of plutonium and recommended that it be treated as a hazardous waste substance rather than a resource.

To the nuclear establishment in India, what is most important about plutonium is its 'tremendous potential … for unlocking the huge energy reserves of our uranium and thorium resources' (P.R. Roy 1989, 1). This potential is because plutonium is capable of fuelling breeder reactors and making possible the three-phase programme envisaged in the 1950s by Homi Bhabha. It is described as having 'a key role to play in the development of atomic energy in India' (B. Raj 2009, 142). Inasmuch as the nuclear establishment is always looking to the (far) future, plutonium rivals uranium in its importance for the atomic energy programme. Because plutonium-fuelled breeder reactors could produce more fuel than they consume (see Appendix 1 on nuclear reactor types), one former member of the Atomic Energy Commission has compared the reprocessing of spent nuclear fuel—the process through which plutonium is produced—to an akshayapatra, the bottomless vessel that always held food for the Pandavas when they were in exile in the forest (N. Srinivasan 1996, 7).[1]

In pursuit of this supposedly inexhaustible source of energy, the DAE has built reprocessing plants at Trombay, Tarapur and Kalpakkam. Little is known publicly about how efficiently these have operated; what little has been revealed suggests that these facilities have been shut down for long periods of time. Even assuming that these plants operate efficiently, the cost of producing plutonium at these facilities has been enormous, and estimated at close to Rs 8000 per gm. This cost is, however, not actually included in the cost of generating electricity at either the PHWRs—where it would constitute part of the waste-management costs—or at fast breeder reactors—where it would constitute part of the fuelling costs. Instead, it is borne by the government. Costs aside, the DAE claims that the plutonium, when used as fuel in breeder reactors, would produce more plutonium which, in turn, could fuel more breeder reactors, and so on, thereby being capable of generating hundreds of thousands of MW of nuclear power by the middle of this century. This imposing edifice, however, has leaky plumbing: in its haste to project large amounts of nuclear electricity, the DAE has not been careful about accounting for the plutonium needed to fuel them nor the time it takes to build reactors. Its calculations assume, in effect, that once an adequate amount of plutonium has been produced, it would instantaneously be transformed into a breeder reactor (Ramana 2010).[2]

BOX 4.1

REPROCESSING TECHNOLOGY

When a reactor (a PHWR or an LWR) operates, energy is produced through the fission of uranium or plutonium.[3] Each such fission event results in the production of two lighter elements. These fission products are usually highly radioactive. Thus, the spent fuel that has been irradiated in nuclear reactors consists mainly of the uranium that has not undergone fission, the plutonium that has been produced by neutron absorption and subsequent decay, and fission products. The purpose of reprocessing is to recover plutonium and uranium from this spent fuel.

Due to the high levels of radioactivity in it, spent fuel generates a large amount of heat. So, it is first stored in water pools for cooling. This spent fuel is then treated in batches; dealing with each batch of spent fuel is called a campaign. The first step after cooling is to remove the cladding that covers the uranium, the plutonium and the fission products in the fuel rods. This can be done in two ways. In the first, the clad is dissolved in a chemical dissolvent. Alternately, the fuel is chopped up and put into hot nitric acid. Chopping exposes the surface of the fuel to the nitric acid. The fuel rod contents get dissolved in nitric acid and get mixed into the solution as nitrates. Most of the cladding is left unreacted. Some cladding does get dissolved and has to be separated and processed as nuclear waste. Both processes (de-cladding and dissolution) release radioactive gases.

The current standard method of extracting plutonium and uranium from this solution is called PUREX, an acronym standing for Plutonium and Uranium Recovery by Extraction. The PUREX process employs what is known as a liquid–liquid extraction—solvent extraction and partitioning—method. The idea is to separate compounds based on their relative solubility into two different immiscible liquids—kerosene and an organic solvent called tributyl phosphate (TBP) in the case of the PUREX process.[4] The TBP selectively separates the plutonium and the uranium from the fission products and other products. Uranium and plutonium are separated from one another in yet another extraction operation using the same principle of different solubility. They are then converted into different chemical forms for storage and transportation.

Besides plutonium and uranium, reprocessing also produces three waste streams classified on the basis of their radioactive content as high-level, intermediate-level and low-level wastes. The largest component (by volume) is low-level waste that comprises by volume over 80 per cent of the waste stream; however, this only contains about 0.1 per cent of the total activity from the spent fuel. Intermediate-level waste accounts for over 10 per cent by volume and contains about 1 per cent of the radioactivity (Rodriguez 1996, 56). High-level waste constitutes about 2 per cent by volume but contains nearly 99 per cent of the total radioactivity.

All the radioactivity present in the spent fuel is divided among these different products except for what escapes in a gaseous form during reprocessing. That is, none of the radioactivity is neutralized. Reprocessing is, therefore, not a solution to the problems inherent in dealing with radioactive waste. The volume of radioactive waste produced actually increases, and some of it is released into the environment. Low-level liquid waste from the Power Reactor Fuel Reprocessing facility and the Tarapur Atomic Power Station reactors is released into the sea at Tarapur; marine organisms, such as algae and oysters, show higher concentrations of various radionuclides than naturally found (Rao et al. 2010; Baburajan et al. 1999). Likewise, radionuclides released by the Trombay reprocessing plant have been detected in sediments from Mumbai's harbour (Patel, Patel, and Pawar 1978). In larger plants, radioactive discharges may travel quite far; for example, discharges from the Sellafield reprocessing plant in England have been detected as far away as Norway (NRPA 2002). Therefore, many have termed reprocessing the dirtiest part of the nuclear fuel cycle. Further, the radioactive wastes which are not immediately released into the environment still have to be disposed of in geological repositories (see chapter 8).

ACQUIRING THE TECHNOLOGY

Plutonium’s suitability for making nuclear weapons has been a source of attraction to the nuclear establishment, albeit not one that was publicly acknowledged for the first few decades. But, as many have documented in great detail, from the very inception of the programme, the weapons option was consciously kept open through various choices that the nuclear establishment made (Abraham 1998; Perkovich 1999; Ramana 2003). Nevertheless, the facade of pursuing only the peaceful uses of nuclear energy persisted for decades and so, the only reason to acquire plutonium that was openly admitted was its potential for constructing breeder reactors (see, for example, Bhabha 1958, 406). For both these reasons, getting hold of reprocessing technology was an early aim of the DAE.

Barely four years after the DAE was established as a government department, in July 1958, the AEC decided to build the first Indian reprocessing plant in Trombay (Sundaram, Krishnan, and Iyengar 1998, 90). Even at that time, there was something unique about the location—it was the only one in the world to be located on the outskirts of a major city. These days, Trombay is usually described as a suburb of Mumbai, making the situation even more unusual and hazardous. There was reason for concern: on 29 September 1957, a few months prior to the AEC’s decision, a large explosion had occurred in the tanks holding radioactive waste at the Mayak nuclear fuel–reprocessing plant in the Soviet Union.[5] There is no evidence, however, that risk was a consideration in the siting of the Trombay plant.

At that point, for more than a decade, plutonium had been considered by some as absolutely necessary for the expansion of nuclear power, even though its existence had been known only some years prior. Plutonium was first produced by Glenn Seaborg at a laboratory in the University of California, Berkeley, in 1941.[6] Later, as part of the Manhattan Project that created the first atomic weapons, industrial-scale production of the element had been carried out on the Hanford Site in the United States. During the early years, a couple of different routes—the bismuth phosphate process and then the Redox process—were used to separate the plutonium out. Subsequently, the PUREX process was invented and became the generally accepted method for treating irradiated spent fuel (Rahn 1984, 608–09).

Extensive details about the reprocessing technology were made public as part of the US Atoms for Peace Program and at the 1955 Geneva Conference (described in chapter 1) (Albright, Berkhout, and Walker 1997, 22). France, for example, described the design of the Marcoule Plant where it carried out reprocessing (Patterson 1984, 31), while the United States talked about the Idaho Chemical Processing Plant (Rahn 1984, 609).

The United States was quite happy to do its bit to help the Trombay plant along. Shortly after the decision to construct the plant, Bhabha went on to discuss the design of the plant with US scientists (Wohlstetter 1977, 3–61). Four engineers, three chemists and a health physicist working on the plant were sent to the United States for training (Sabavala 1964, 18). Thanks to the efforts of Edward Stone, the architect responsible for the US embassy in New Delhi, the American company Vitro International became involved in the design and construction of this plant (Kupp 2006, 109). Robert Kupp, the chief nuclear engineer at the company, relates that he had to travel to Bombay on three occasions at various stages during the construction and that he witnessed Bhabha and Stone, ‘two incredible egotists go at it’ (Kupp 2006, 110).

The nuclear establishment’s version of the construction of this plant makes no mention of these inputs. In the words of AEC Chairman Homi Sethna: ‘In 1961, we commenced work for setting up a reprocessing plant at the Centre [that is, Bhabha Atomic Research Centre] *completely on our own and without any foreign collaboration*. The plant was successfully commissioned in 1964, making India the fifth country in the world with reprocessing facilities’ (Sethna 1979, 4) (our emphasis). Similarly, the official DAE history of the first fifty years of the atomic energy programme in the country says: ‘It became one of the most important landmarks in the Indian programme, that this plant entirely designed and built by Indian engineers, under the leadership of H. N. Sethna and N. Srinivasan could be completed and commissioned by mid-1964’ (Sundaram, Krishnan, and Iyengar 1998, 90).

This is not to say that the DAE engineers did nothing on their own. Even if they had obtained a ready-made plant from elsewhere, they would have had to adapt it to local conditions. For example, a computer that is imported has to be made to work in a different temperature regime, with potentially more dust in the environment, and using a power supply with fluctuating voltages. All these problems demand modifications that change the computer from being purely imported to partly indigenous. The same would be the case of a complex technological artefact like a reprocessing plant. Further, there was no reprocessing plant that the DAE could buy. At the same time, the DAE has, by and large, tried to portray *all* its activities as examples of ‘self-reliance’ or ‘indigenous development’. Because of this, it has downplayed—or, as in this case, completely negated—the inputs it has received from elsewhere.

The DAE spared no effort in making sure that this achievement was widely known.[7] On 3 August 1964, Bhabha gave a talk titled ‘Development of Atomic Energy in India’ on All India Radio, where he spoke at length about the Trombay facility (Bhabha 1964). This national radio service was, at that time, the dominant source of information and was therefore very influential in shaping public opinion. Bhabha started by describing the plant as one used for ‘treating used fuel elements and extracting from them the very valuable fissile material, plutonium. It is this material which will form the bridge to the use of thorium for the generation of electricity from atomic energy’. He then went on to extol the accomplishments: ‘A plutonium plant is one of the most sophisticated types of chemical plants and has several special features … The design and construction of this plant by Indian scientists and engineers is a considerable achievement. There are only four other countries operating plutonium plants—France, the U.K., the USA, the USSR; Norway also has a small pilot plant’ (Bhabha 1964, 147–48).

REPROCESSING PLANTS

Trombay was the first of three locations where the DAE has reprocessed spent fuel, the other two being Tarapur and Kalpakkam. Trombay is used to reprocess spent fuel from the CIRUS and the Dhruva reactors (DAE 2003a, 11). It is generally assumed that the resulting plutonium is being used for manufacturing nuclear weapons though, in the past, it was used to fuel the fast breeder test reactor and the PURNIMA reactor. The Tarapur and the Kalpakkam reprocessing plants are used currently to reprocess spent fuel from various power plants of the PHWR type.

The Department of Atomic Energy has on more than one occasion announced plans for setting up more reprocessing plants with a larger throughput but this has not happened so far (DAE 1994, 24; 1995a, 2.2).[8] It has also projected sharp increases in reprocessing capacity. The latest of these targets was for a reprocessing capacity of 550 tHM by the year 2010 and of 850 tHM by 2014 (Dey 2003, IT-14/6). The first target was not reached and it is unlikely that the second will.

Trombay

The smallest of the DAE's reprocessing plants is the Trombay plant, designed initially to reprocess 30 tonnes of spent fuel per year.[9] It started functioning in 1964.[10] The first quantities of pure plutonium oxide and the samples of plutonium metal were produced later that year or early the following year (Sundaram, Krishnan, and Iyengar 1998, 90). The plant was formally inaugurated by Prime Minister Lal Bahadur Shastri in January 1965. At the opening ceremony, Shastri 'offered this plant to countries of South-East Asia for reprocessing their fuel in case this was required' (Jain 1974, 397).[11]

While the commissioning of the plant was widely advertised, the DAE was secretive about the fact that the plant 'failed to work properly for almost seven years after formal commissioning. The chief problem was the separation of plutonium from the fission products. The concentration of the latter in the final product continued to be too high for the material to be handled and used for any purpose' (Parthasarathi 2007, 17). This presumably was solved by the late 1960s because the plant produced enough plutonium for the test reactor PURNIMA (see chapter 1), and for the 1974 and 1998 nuclear weapons tests at Pokhran.

The Trombay reprocessing plant used the PUREX process (see this chapter, Box 4.1) with 30 per cent tributyl phosphate as solvent (Prasad and Kumar 1977, 3). It was intended to deal with spent fuel from the CIRUS reactor—whose fuel was uranium-metal-sheathed in aluminium—and so, the cladding was removed using a chemical process. Because metallic fuel gets distorted, the fuel cannot be left inside the CIRUS reactor for extended periods and has to be replaced when the burn-up is relatively low (AECL

1997, 217).[12] This means that the concentration of fission products and, thereby, the levels of radioactivity in the spent fuel rods will be low.

Nevertheless, the mixture of hot acid and numerous chemicals intensely corroded the plant equipment and the piping and, as a result, the plant had to be shut down for decontamination and partial decommissioning (Prasad and Kumar 1977, 3). The process took over a decade, from 1972 to 1983 (*Nuclear Fuel* 1983; Subramanian 1998, 92). The 'cells' where the reprocessing used to be done were fully emptied out, cleaned, new equipment installed and piping laid out (Nair and Prasad 1991, 68). This process generated about 300 tonnes of solid waste, about 60,000 litres of liquid waste with medium-level radioactivity and about 13 million litres of liquid waste with low-level radioactivity (MacLachlan 1985, 11). When the plant was recommissioned, its capacity was increased from 30 tonnes/year to 50 tonnes/year.

Tarapur

The next reprocessing plant to be constructed, the PREFRE facility, was located in Tarapur and has a capacity of 100 tonnes/year. Construction started in the early 1970s and the plant was commissioned in 1977 (Sundaram, Krishnan, and Iyengar 1998, 90). The first batch of spent fuel rods was reprocessed in April 1978 (Mirchandani and Namboodiri 1981, 73). PREFRE was built to reprocess up to 100 tonnes of spent fuel each year. Originally, the plant was intended to reprocess spent fuel from the boiling water reactors at Tarapur and from the pressurized heavy water reactors in Rajasthan and elsewhere. But following the 1974 nuclear test, the US Congress passed the Nuclear Non-Proliferation Act in 1978, as a result of which the United States forbade the reprocessing of spent fuel from the Tarapur BWRs.[13]

For the first few years, PREFRE reprocessed only spent fuel rods from CIRUS (DAE 1982, 31). Only in 1982 did PREFRE begin to reprocess PHWR spent fuel from Rajasthan (DAE 1983, 31). This continued till 1986 and after it had 'completed the third campaign … [of] spent fuel bundles' from the Rajasthan Atomic Power Station, it was shut down for 'an extended maintenance outage' (DAE 1986, 3.19). Since then, it appears that reprocessing of spent fuel from RAPS has stopped. But it has reprocessed spent fuel from the Madras Atomic Power Station reactors (Sundaram, Krishnan, and Iyengar 1998, 90). In 2005–06, PREFRE received its first spent fuel shipment from Narora (DAE 2006a, 34).

Because the RAPS and the TAPS spent fuel are not reprocessed, they are stored in away-from-reactor (AFR) facilities on location (V.S. Srinivasan 1995, 59; Kulkarni, Soni, and Agarwal 2003, 30–31). The DAE's reason for storing rather than reprocessing RAPS spent fuel may partly be because of the institution's general aversion to IAEA safeguards. While reprocessing spent fuel from the RAPS I and II reactors—that are under a safeguarding agreement with the International Atomic Energy Agency—PREFRE also comes under safeguards, and the IAEA personnel carry out inspections (M.R. Srinivasan 2002, 242). The plutonium separated from reprocessing RAPS spent fuel in the 1980s was placed under monitored storage (OTA 1995, 117).

The PREFRE plant appears to have been performing quite poorly, especially in the first two decades. In the 1990s, it was reportedly running 'substantially' below its nominal capacity, with an average efficiency level of 25 per cent (Hibbs 1995, 18). According to P.K. Iyengar, the chairman of the Atomic Energy Commission, and A.N. Prasad, director of the Bhabha Atomic Research Centre, a single campaign consisted of 'less than 40' tonnes of spent fuel and could take 'six to eight months to about one year' to complete (Hibbs 1992b, 8). Since then, several annual reports of the DAE mention PREFRE as undergoing revamping or being started up after revamping, indicating that it must have been shut down for extended periods of time.[14] Reports of poor performance continued and, in March 2003, it was reported that 'PREFRE had been shut for an entire year, and would remain idle for another six months, because of technical problems' (Hibbs 2003, 9).

In January 2011, Prime Minister Manmohan Singh 'dedicated' another reprocessing line with 100 tonnes/year capacity at Tarapur (ToI 2011). With this addition, Tarapur appears to have a maximum reprocessing capacity of 200 tonnes/year.

Kalpakkam

On 20 July 1978, Prime Minister Morarji Desai informed the Rajya Sabha that a plutonium-reprocessing plant was 'proposed to be constructed' at Kalpakkam (Mirchandani and Namboodiri 1981, 72). This decision had evidently been taken before there was any experience with operating the Tarapur PREFRE plant. The Kalpakkam Atomic Reprocessing Plant (KARP) was granted financial sanction by the government in 1983 (DAE 1987b, 19) and the cost was pegged at Rs 0.96 billion (DAE 1997b, 20). It was reportedly set up primarily to reprocess the spent fuel from the Madras Atomic Power Station (Hibbs 1997a, 8).

KARP is reported to have two reprocessing lines each of which is designed to deal with 100 tonnes of spent fuel each year. The two lines were not meant to be run in parallel; the first was supposed to operate for seven to eight years and then be decommissioned, at which time the second line would take over (Hibbs 1997a, 8).[15] Kalpakkam also has a smaller facility (sometimes called a hot cell or a Lead Mini cell) for reprocessing spent fuel from the fast breeder test reactor. Spent fuel from the PFBR under construction will be reprocessed at the Fast Reactor Fuel Cycle Facility that is also to be constructed in the Kalpakkam complex.

Operation of the plant was originally planned for 1993 (DAE 1993, 11), but was delayed due to quality control problems in piping and other equipment (Hibbs 2003). The plant was finally commissioned in 1998, taking about sixteen years in all (DAE 2000a, 25).

This period of construction—from the early 1980s to the late 1990s—was a hard one for the nuclear establishment. There were public protests and oppositional movements, including the successful ones that put an end to plans for nuclear reactors in Kerala; there were major accidents, such as the disastrous fire in the Narora reactor; there were embarrassments, including the collapse of the containment dome at Kaiga; and there was some financial pressure on the establishment due to general cutbacks on various forms of government spending that accompanied economic liberalization. Perhaps to counteract those and to bolster its image, the DAE went into advertisement mode as KARP approached completion.

In 1996, it released a glossy brochure filled with pictures of imposing buildings, intricate process equipment and visiting luminaries (DAE 1996b). The aim, evidently, was to impress the reader with euphoric descriptions and complicated jargon that would be incomprehensible to most. The fuel handling system, for example, is described as ‘a mechanical marvel’, while the subheading of the page with pictures of process piping is ‘Bewildering Complexity’. Acronyms without expansions abound: SS, CS, HEPA, CWMF, GTAW, and so on. There is a photo of Hans Blix, director general of the IAEA, peering up at something outside the frame with the quote, ‘I am most impressed with this important result of advanced Indian Science and Engineering’.

Most impressive of all are the myriad numbers. The brochure informs us, for example, that the plant has 25,000 joints and 85 km (approximately the same as the distance between Madras and Kalpakkam, we are told) of in-cell piping, that the fuel storage pond can hold 8.7 lakh litres of demineralized water, and that it used 66,000 cubic m of concrete, 10,000 tonnes of TOR steel (without explaining what TOR stands for) and 29,000 tonnes of cement (DAE 1996b). ‘India in the 1950s fell in love with the idea of concrete’, wrote Sunil Khilnani (1997, 61). The 1996 brochure and subsequent publications reveal that the DAE is yet to get over its love-for-concrete phase that marked the 1950s.

These lists of numbers have another function: they cater to what historian Vinay Lal identifies as the national obsession for records. And this ‘fetish for records … is in the first instance a propensity towards numbers’ (Lal 2005, 5). Records, especially those that measure Indian achievements in comparison to other countries, are particularly important to the elite. ‘It is the political and economic elite in India who reminds us that India stands third in the strength of its scientific manpower, that it is a member of the “Nuclear Club”, that its software engineers have conquered (so to speak) the heights of Silicon Valley, and that it is the only Third World nation to join a few of the post-industrial countries as an exporter of satellite and rocket technology’ (Lal 2005, 7).

This elite group has been a stable source of support for the nuclear establishment. They are the ones who are most concerned about India’s place in the world, and who see nuclear power as elevating that status. They are also the most anxious to be seen as modern, and the public status of nuclear power as representing advanced technology is perfectly suitable. The elite have also been the most concerned about where India will be in the future, rather than where it is now. This characteristic attracts them to the nuclear establishment, because of its ability to promise extremely large amounts of energy, and that, too, using modern technology. In his PhD dissertation examining energy planning in India, scholar Manu Mathai argues that ‘the success of such projections in convincing or at least silencing critics is reflective of a deeper allegiance within India’s wider elite to a similar future-tense orientation in evaluating social circumstance’ (Mathai 2010, 248).

It is this constituency that the DAE has cultivated through its brochures and press releases that are full of grandiose adjectives describing the scale, the complexities and the uniqueness of its activities.[16] Many of them proudly describe that India was the third or the sixth country in the world to have successfully performed some task or the other. One example that has already been mentioned is of the announcements about India’s being the fifth country to be able to reprocess spent fuel. But, even into the new millennium, the DAE’s announcement about the construction of the Solid Storage Surveillance facility in Tarapur includes the additional piece of information that ‘India is the fourth nation in the world to have such a hi-tech facility’ (DAE 2000b). Or that vitrification—the mixing of radioactive wastes with glassy materials for storage—is ‘a complex technology possessed by a few nations only’, and that it has been successfully developed at the Bhabha Atomic Research Centre (DAE 2003b).

COSTING PLUTONIUM

The cost of reprocessing in India is reminiscent of the Hindi proverb ‘*dhobi ka kutta, na ghar ka, na ghat ka*’ (the washerman’s dog belongs neither to the house nor to the riverbank). On the one hand, the Nuclear Power Corporation, while analysing the economics of PHWRs, says that ‘the cost of waste disposal [that is, reprocessing] has been assumed to have trade off [*sic*] with the amount of reprocessed fuel [that is, plutonium] generated for next stage of nuclear power programme’ (Nema 1999). On the other hand, while analysing the economics of breeder reactors, ‘plutonium and depleted uranium are assumed to be available free of cost’ by the Indira Gandhi Centre for Atomic Research (Govindarajan 2003, IT-23/1). These two assumptions imply that the cost of reprocessing falls between the proverbial cracks, right into the citizen’s lap.

Perhaps because reprocessing has been offloaded to the government, there is simply no public estimate of how much it costs to produce plutonium. This crucial figure was necessary to examine the economics of breeder reactors (described in chapter 6). Because it was not available, a few years ago, my economist colleague Suchitra and I set out to calculate this from whatever data was available in the public domain.

There was a secondary reason—to see whether the DAE confirms or disproves findings about reprocessing in other countries. In the United States, a number of studies since the 1970s have shown that reprocessing is far more expensive than the alternatives (see, for example, Cochran 1974; Feiveson, von Hippel, and Williams 1979; National Research Council 1996; Bunn et al. 2005; Deutch et al. 2003). Adverse economics was an important factor for the United States to stop reprocessing civilian spent fuel (von Hippel 2001). The primary reason is the enormous capital cost of the reprocessing facility.

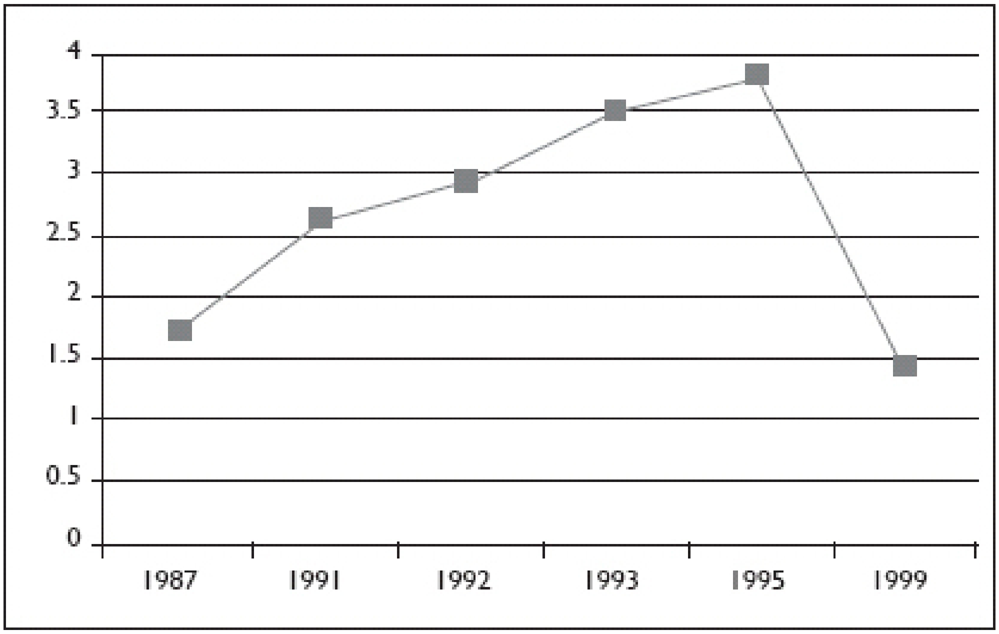
Although it has not conducted any rigorous study to support its assertions, the DAE claims that it is an exception to these international findings and 'Indian reprocessing and storage costs in terms of installation and operation are substantially lower' (Balu and Ramanujam 1999, 59). Indeed, in 1996, the director of BARC averred that '*economic considerations dictated the need for spent fuel reprocessing in India'* (A.N. Prasad 1996, 13) (our emphasis). The only potential justification for this unexpected conclusion could be the lower cost of construction in India: AEC Chairman Sethna stated in 1979 that the cost of the Trombay plant 'was less than half the estimated cost of similar capacity plant under construction at that time in another country. Our subsequent experience in the construction of a power reactor reprocessing plant [that is, the Tarapur plant] has confirmed our ability to set up and operate small capacity reprocessing plants at costs lower than indicative reprocessing plants elsewhere in the world' (Sethna 1979, 4–5).

The lower cost of constructing the Trombay plant may have something to do with the techniques used for constructing CIRUS and the plutonium plant. The description of these techniques by Robert Kupp of Vitro International, who found them 'amazing', is something most will find familiar: 'A small … mixer dumped its load of concrete on the ground. The concrete was then loaded by a man into a circular pan, placed on the head of a woman, waiting in a long line, who carried and dumped it into a six foot thick shielding wall … Children of these women were playing on the gravel piles, cement forms, and anywhere else that seemed exciting' (Kupp 2006, 110).[17]

The question that Suchitra and I proceeded to examine was, given this lower construction cost, what did reprocessing cost in the DAE's facilities and what was the cost of producing plutonium (Ramana and Suchitra 2007). We chose to focus on the Kalpakkam facility, because it was the most recently constructed plant and, according to the DAE, was to serve as a standard design for future plants (Dey 2003, IT-14/6).

To start with, we had to know what it had cost to construct KARP. The original financial sanction of the KARP plant was Rs 0.96 billion (DAE 1997b, 20). As may be expected, this went up subsequently but then, as shown in [18]

FIGURE 4.1: ESTIMATED COST OF KALPAKKAM REPROCESSING PLANT IN VARIOUS DAE DOCUMENTS IN BILLIONS OF RUPEES



The sudden decline seemed inexplicable and to check if that were really the case, Suchitra and I systematically collected the DAE's Performance Budgets from 1983–84 to 1999–2000.[19] When the annual expenditures on KARP listed in them were added up, it turned out that the DAE had spent

Rs 5.58 billion, much more than any of the figures mentioned in DAE documents, and nearly four times the final amount of Rs 1.43 billion mentioned in DAE documents. But this figure is in terms of rupees from different years (mixed year rupees); when adjusted for inflation to express it in terms of rupees for a fixed year, which we chose to be 2004, KARP's construction cost turned out to be Rs 12.86 billion (2004 rupees).[20]

There are a number of other cost elements. These relate to operations and maintenance, decommissioning and waste disposal. In most cases, there were no estimates for KARP, but there was some budget data for PREFRE that we extrapolated from (for details see Ramana and Suchitra 2007, 461–63). However, these are quite low compared to the construction cost. Taking all these together, we found that at a 6 per cent discount rate, it costs Rs 29,010 to reprocess each kilogram of PHWR spent fuel.[21] Assuming a very high efficiency of extraction—that 99 per cent of the plutonium present in the spent fuel is recovered—this translates to a cost of Rs 7814 to obtain each gram of plutonium.[22]

When combined with the finding that breeder electricity will not be competitive even with PHWRs (see chapter 6), even with much higher uranium prices (Suchitra and Ramana 2011), there is simply no economic case for reprocessing. What, then, could motivate reprocessing? One possible answer was suggested by a former member of the AEC in 1996. Speaking at a function to commemorate the cold commissioning of KARP—one of the stages before it starts actually reprocessing spent fuel—he stated: 'as far as the department [of atomic energy] is concerned, reprocessing has represented … "a spirit of adventure"' (N. Srinivasan 1996, 8). It is quite conceivable that the engineers and scientists in the DAE find working with radioactive materials and corrosive chemicals an adventure, but should it be at the expense of the citizen?

PLUTONIUM ACCOUNTING AND FAST BREEDER GROWTH

The DAE does offer one other, non-economic, rationale for extracting plutonium—plutonium is required to fuel breeder reactors, and breeder reactors are going to form a significant component of our energy production in the future (Bhabha and Prasad 1958; Chidambaram and Ganguly 1996). In the last decade, the DAE has quantified this assertion, projecting in 2004 that breeder reactors would constitute roughly 20 per cent of India's electricity-generating capacity by mid-century (Grover and Chandra 2004; 2006, 2845).

This projection has gone up even more after the US–India deal. Though the detailed assumptions behind these larger figures have not been made public, the DAE has made it clear that the methodology used is the same as laid out in earlier papers (Grover and Chandra 2004; Grover and Chandra 2006). The difference, therefore, has to be in the assumptions about how much PHWR and LWR capacities are assumed. The PHWR produces much more plutonium than the LWR and, therefore, breeder growth would be faster in the former case; the DAE has estimated that, over a fifty-year period, the breeder capacity based on PHWRs would be four times the breeder capacity based on LWRs (Grover, Purniah, and Chandra 2008, 77). Since the DAE's methodology exaggerates the rate at which breeder reactors can be constructed, the more recent projections too will not be realizable.

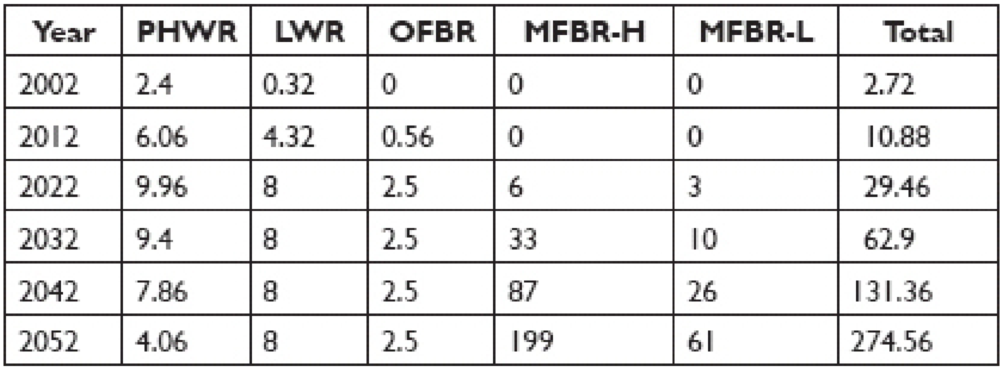
Let us start with what the DAE does. Its elaborate scenario for constructing a large number of breeder reactors commences with the prototype fast breeder reactor under construction at Kalpakkam. The PFBR uses as fuel a mixture of plutonium and uranium oxides, or MOX fuel, which has the advantage of having been used in most large breeder reactor demonstration projects around the world. Therefore, the DAE can piggyback on the experience of other countries. The problem was that the PFBR design had a low breeding ratio of 1.04 (IGCAR 2004, 1.18).[23] The breeding ratio being just over unity implies that the PFBR would produce barely more plutonium than it would consume as fuel. Thus, it was not conducive to the projection of rapid growth of nuclear power based on fast increases in plutonium stocks.

So, when it came to projecting a large nuclear capacity for the future, the DAE simply assumed that it would be able to develop a design for a breeder reactor using a fuel made of just plutonium and uranium metals that has the potential for a higher breeding ratio.[24] Since the DAE had no designs for a breeder reactor of this kind, the breeding ratio of 1.582 and other parameters were taken from studies by the International Nuclear Fuel Cycle Evaluation (INFCE) group put together by the International Atomic Energy

Agency in the late 1970s (INFCE 1980).[25] These were theoretical studies, and their figures were not really based on actually constructed reactors, but projections by breeder reactor enthusiasts.[26]

Based on these parameters, the DAE projected that by 2052 it would construct hundreds of breeder reactors; when combined with the other kinds of reactors that it envisioned constructing or importing, the total capacity would amount to 275 GW (Grover and Chandra 2006, 2844).[27] Table 4.1 gives the break-up of this figure. The different columns refer to the installed capacities of pressurized heavy water reactors, light water reactors, breeder reactors using MOX fuel (OFBRs), and Metallic Fuel using plutonium obtained by reprocessing spent fuel from PHWRs and LWRs (MFBR-H and MFBR-L). Note that the 2012 projection has itself not materialized.

TABLE 4.1: DAE NUCLEAR CAPACITY PROJECTIONS (GW)



Year	PHWR	LWR	OFBR	MFBR-H	MFBR-L	Total
2002	2.4	0.32	0	0	0	2.72
2012	6.06	4.32	0.56	0	0	10.88
2022	9.96	8	2.5	6	3	29.46
2032	9.4	8	2.5	33	10	62.9
2042	7.86	8	2.5	87	26	131.36
2052	4.06	8	2.5	199	61	274.56

Source: Grover and Chandra 2006, 2844.

The methodology employed to calculate the MFBR-H and MFBR-L components is based on using the breeding ratio to calculate the doubling time, which is the time that the breeder reactor takes to produce sufficient plutonium to construct the core of an identical breeder reactor. The doubling time assumed for the MFBRs is 8.9 years.

This methodology of doubling times is widely used by breeder proponents elsewhere and is a reasonable approximation to what the *theoretical* growth rates might be if there were already a large plutonium stockpile and a large flow of plutonium coming from LWRs or PHWRs. However, in the absence of these two conditions, the rate at which breeder capacity can be set up will be strongly constrained by the fuelling requirements of existing reactors in the initial years. This is the case in India and, therefore, the use of the simple doubling time methodology will lead to exaggerated growth figures. Let us see why.

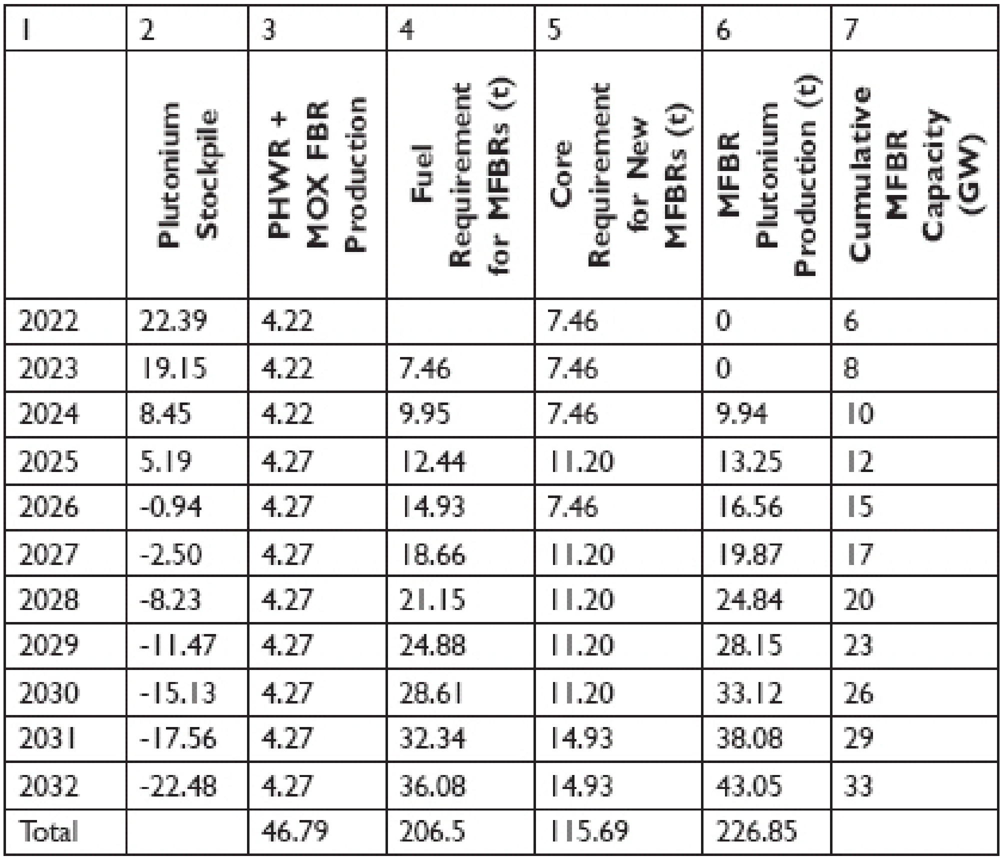
The DAE implicitly assumes that, in 2022, there will be sufficient plutonium separated from spent fuel produced in PHWRs to set up 6 GW of MFBRs (Table 4.1). Here again, this initial capacity with which the growth of MFBRs is projected is itself erroneous because it does not take into account the plutonium required for setting up and fuelling the five OFBRs (oxide-fuelled fast breeder reactors), which have very low breeding ratios (for details see Ramana and Suchitra 2009). If those are taken into account, then the 2022 MFBR capacity will only be 1 GW, even with optimistic assumptions.

The initial figure itself is impossible. But, for the sake of argument, assuming that by 2022 the DAE would somehow set up 6 GW of MFBR capacity—using plutonium derived from reprocessing indigenous PHWRs—my collaborator Suchitra and I examined how fast this could grow. According to the DAE's projections, the 6 GW of MFBR capacity in 2022 derived from PHWR spent fuel would lead to 33 GW by 2032, 87 GW by 2042, and 199 GW by 2052 (Grover and Chandra 2006, 2844). How much plutonium would be needed to meet these targets?

Setting up each GW of MFBR capacity requires 3.732 tonnes of fissile plutonium—those isotopes of plutonium, primarily plutonium-239 and plutonium-241, that undergo fission even when struck by low energy neutrons. This inventory of 3.732 tonnes is sufficient for the core and the first reload; subsequently, it requires 1.244 tonnes of fissile plutonium every year as fuel (INFCE 1980, 177–79).[28] To set up 6 GW, therefore, the DAE would require 22.4 tonnes of fissile plutonium. To demonstrate the problems with the DAE's methodology, we assumed that in the year 2021, the DAE would have 44.8 tonnes of fissile plutonium, twice the amount required. Half of this would be used to set up 6 GW of breeder reactors, and the remaining would be retained as inventory for fuelling.

The growth of breeder capacity is linked to the availability of plutonium. There are three sources of plutonium production: PHWRs, OFBRs and MFBRs. Based on the capacities of these different reactors assumed by the DAE (see Table 4.1), and adopted by us, the PHWRs and the OFBRs will, together, produce 4.23 tonnes of fissile plutonium every year. The MFBRs can add 1.656 tonnes of fissile plutonium every year per GW of capacity. So, the higher the MFBR capacity, the bigger will be the plutonium production. This is, after all, the idea of breeder capacity growing rapidly. But, this plutonium will not be available immediately. There is an inevitable lag because of the time involved in carrying out the various steps needed to produce it: withdrawing the spent fuel from MFBRs, reprocessing and separating the plutonium from this spent fuel, and fabricating it into fuel. This is called the out-of-pile time (OP). The DAE assumes that the OP will be just one year. This is extremely implausible but, in the spirit of pursuing the argument to its logical conclusion, we followed this assumption and accordingly did the plutonium accounting. The annual plutonium credits and debits are listed in Table 4.2.

TABLE 4.2: FISSILE PLUTONIUM BALANCE FROM 2022 TO 2032 FOR THE DAE SCENARIO



1	2	3	4	5	6	7
	Plutonium Stockpile	PHWR + MOX FBR Production	Fuel Requirement for MFBRs (t)	Core Requirement for New MFBRs (t)	MFBR Plutonium Production (t)	Cumulative MFBR Capacity (GW)
2022	22.39	4.22		7.46	0	6
2023	19.15	4.22	7.46	7.46	0	8
2024	8.45	4.22	9.95	7.46	9.94	10
2025	5.19	4.27	12.44	11.20	13.25	12
2026	-0.94	4.27	14.93	7.46	16.56	15
2027	-2.50	4.27	18.66	11.20	19.87	17
2028	-8.23	4.27	21.15	11.20	24.84	20
2029	-11.47	4.27	24.88	11.20	28.15	23
2030	-15.13	4.27	28.61	11.20	33.12	26
2031	-17.56	4.27	32.34	14.93	38.08	29
2032	-22.48	4.27	36.08	14.93	43.05	33
Total		46.79	206.5	115.69	226.85	

Source: Ramana and Suchitra 2009, 5032.

What we found was that if one assumed the same growth rate as the DAE from 6 GW in 2022 to 33 GW in 2032, the plutonium stockpile, listed in column 2, would actually go down from 22.4 tonnes to *minus* 22.48 tonnes. In essence, the reason for this decrease is that if a breeder reactor were to be set up in, say, 2025, the plutonium for its core must be available and set aside at least a year in advance. Once the reactor starts, the first batch of spent fuel can be removed from the reactor only when the reactor is shut down for refuelling each year. It then takes another year, the assumed OP, for this spent fuel to be reprocessed and the extracted plutonium fabricated into fuel. In all, therefore, there is a lag of roughly three years, even in theory, between the time a certain amount of plutonium is committed to a breeder reactor and it reappears in the form of separated plutonium for refuelling the same reactor and setting up new breeder reactors. But in the meanwhile the reactor that has been set up has to be fuelled with plutonium from the existing stockpile.

The DAE does not publicly reveal enough details about its projection methodology for us to know what errors they have committed. In February 2009, I emailed the primary author of the DAE's projections, asking if he could share these details, but received no reply. The likely source of the problem is that their projections don't take into account the time lag described above.

Be that as it may, basically, what we demonstrated was that the DAE's projections were theoretically impossible. It is unlikely to have adequate quantities of plutonium to set up its proposed 6 GW from PHWR spent fuel in 2022. Further, even if the DAE were somehow to obtain sufficient plutonium to set up 6 MFBRs, the addition of new MFBRs at the rate at which it envisions will result in negative plutonium balances. In other words, the DAE would have to construct new breeder reactors and fuel them from thin air. This is not a matter of difference in assumptions but simply an impossible and absurd projection.

Even with the same optimistic assumptions as the DAE—especially that the OP is one year—a more careful accounting of plutonium, so as to ensure that there are no negative plutonium balances, yields a result that is 60 per cent lower than that of the DAE. Now, there are technical reasons why the OP may be much more than one year. The reprocessing of breeder reactor fuel is fraught with problems. One is due to the use of sodium as coolant. Since sodium reacts violently with water, all sodium has to be carefully removed from the spent fuel before it can be stored in a pool of water (Benedict, Pigford, and Levi 1981, 527).[29] The second problem is to do with the high plutonium content in the spent fuel, which means that only small amounts of spent fuel can be processed at a given time within a small volume to avoid criticality (NEA 2005b, 186). There are no commercial-scale facilities that have dealt with large quantities of fast breeder reactor (FBR) spent fuel—for good reason—and so, there is no experience to draw upon. All of this implies that an OP of three years might be more realistically achievable. In that case, the *theoretical* breeder capacity will only be 17 per cent and 3 per cent of the DAE's projections of MFBR and the total electricity-generation capacity respectively. Even if a similar breeder construction effort were mounted using plutonium from imported LWRs, the contribution to electricity generation would be similarly small.

The only constraint that we had assumed was the availability of plutonium, that is, that there would be no delays because of infrastructural and manufacturing problems, economic disincentives due to the high cost of electricity, or accidents. Including these real-life constraints that are familiar to all only reinforces our conclusion that nuclear power growth based on breeder reactors would be slow at best, and would never constitute a major source of electricity in India for several decades, if not longer.

BOX NO. 4.2

THE PLUTONIUM-MINING ARGUMENT

In 2006, at the height of the debate over the US–India deal, Anil Kakodkar, chairman of the Atomic Energy Commission, offered a new justification for reprocessing: 'Spent fuel, if deposited in repositories for long-term disposal would, over a period of time, become a virtual plutonium mine once most of the radioactive components decay out. This can thus become a serious security issue over a long term' (Subramanian 2006d). In other words, because all nuclear reactors produce plutonium during operations, their spent fuel could become a source of fissile material for potential use in nuclear weapons. This is true of course but, in a strictly technical sense, this fact does not constitute a valid argument for reprocessing.

But, before getting into the technical problems with the argument, it may be worth reminding ourselves of a few obvious truths, simply because they are not often articulated in the mainstream media. To start with, for the AEC, which has been espousing nuclear weapons for decades, preaching about the insecurity caused by plutonium is hypocritical, to say the least (Suchitra and Ramana 2006, 4850). If indeed one is serious about future security concerns, the obvious thing to do is to stop producing any more plutonium, in other words, cease reprocessing. Carried to the next logical step, concern about the plutonium and spent fuel would imply the shutdown of all nuclear reactors. This would, of course, put the DAE out of business.

The DAE is also being hypocritical because it is currently sitting, figuratively speaking, on a pile of plutonium as a result of reprocessing and fashioning this plutonium into nuclear weapons, while pontificating about unspecified people accessing plutonium. Further, there are far more serious security concerns because of plutonium being extracted at reprocessing plants. It is not only more easily accessible since it is above the ground, but it is, in theory, possible to access it today. This is much more dangerous than the situation foreseen—that, at some undefined time in the future, the spent fuel which has been buried deep in the earth will become an attractive source of plutonium.

Now let us turn to the technicalities. Spent fuel contains a small quantity of plutonium (roughly 3.75 kg in each tonne) but it also has fission products. The latter are fiercely radioactive, and anyone near a sizeable quantity of spent fuel would get a lethal radiation dose in a matter of minutes. It will take at least several decades, if not centuries, for the spent fuel to become approachable without it being a fatal hazard. Only after this period could the spent fuel emplaced in geological repositories become a source of plutonium. However, for this to be an *attractive* source of plutonium, acquiring it from such repositories must be easier than alternative means; this is almost never the case (Lyman 1994, 1998).

Two possible scenarios may be considered. One is that the nation that has a geological repository also has an active nuclear fuel chain, with operating reactors and other nuclear facilities. Then, there will be a ready supply of spent fuel available at reactors. Further, if, as in the case of India, there are reprocessing plants as well, there would also be stockpiles of separated plutonium. Spent fuel in a sealed geologic repository well below the surface, then, would be a relatively unattractive source of plutonium, assuming that repositories were guarded and protected just like reprocessing plants and nuclear reactors.

The second possibility is that nuclear power has been phased out and neither operable reactors nor retrievable spent fuel storage facilities exist. In this case, the only means of acquiring spent fuel other than mining the repository would be the construction and operation of production reactors and associated front-end facilities (for example, uranium mining and fuel fabrication) from scratch. While this would at face value seem more difficult, the catch is that both mining plutonium from geological repositories and the alternative, that is, producing plutonium from scratch, would have to be done in a clandestine fashion without being detected. Monitoring and detection is far easier at a limited number of known repositories, whereas clandestine nuclear production could go on virtually anywhere. Only when the scale of the clandestine production becomes very large—roughly at a rate comparable to the highest rate of production achieved by the superpowers during the Cold War—would its detection achieve a level of certainty that is comparable with plutonium mining (Lyman 1994).

THE POWER TO ANNIHILATE

The other attraction of plutonium for the DAE and sections of the elite is its ability to inflict mass death and destruction. And in a world of strategists obsessed with notions of deterrence and second strike, more plutonium is translated to more weapons that could be built. Since 1964–65, when the Trombay plutonium plant started producing plutonium, the DAE is estimated to have accumulated somewhere between 350 and 700 kg (as of 2011) of weapon-grade plutonium, sufficient for 70–140 nuclear weapons (IPFM 2011, 18).[30]

All this is from the spent fuel produced by the CIRUS and Dhruva reactors that has been reprocessed at the Trombay plant. The term weapon-grade is applied to plutonium from these reactors because the concentration of higher isotopes of plutonium would be small.[31] This material is better suited to making nuclear weapons than plutonium from power reactors because the latter has a greater concentration of higher isotopes of plutonium. However, J. Carson Mark, former director of the theoretical division of the US Los Alamos National Laboratory has argued that even reactor-grade plutonium—which has higher concentrations of the higher isotopes of plutonium—can be used to make a nuclear explosive (Mark 1993). In 1994, the US Department of Energy announced that a US nuclear test in 1962 had used reactor-grade plutonium. There is even some speculation that one of the tests conducted by India in May 1998 used reactor-grade plutonium (Ramachandran 1999, 50). During the negotiations over the US–India nuclear deal, the DAE refused to allow this material to be put under international safeguards, thereby leaving open the possibility that this plutonium could be used in weapons. The estimated stockpile of reactor-grade plutonium is between 3.8 and 4.6 tonnes, sufficient for several hundred nuclear weapons (IPFM 2011, 23).

PLUTONIUM AND THE FUTURE OF NUCLEAR POWER IN INDIA

The DAE maintains that the primary purpose of producing reactor-grade plutonium is to fuel breeder reactors. This mantra of a three-phase programme was enunciated half a century ago, in a different era, without the benefit of the plentiful albeit negative experience that is now with us. The government, for its part, is trapped in this commitment to a plutonium-powered future, much in the manner of other governments who have been trapped by commitments to reprocessing (Walker 1999).

The DAE's attraction to plutonium makes little sense in light of the many hazards it poses to human health, its contribution to making weapons of mass destruction and the huge expense involved in extracting the substance from highly radioactive spent fuel. Even if one were to desire the continued growth of nuclear power, there is no good reason, now or in the foreseeable future, to pursue reprocessing and the extraction of plutonium. The DAE, it seems, is lost in the dreary desert sand and has not found the way to the heaven that the poet Rabindranath Tagore (1913) sketched out in his *Gitanjali*:

> Where the clear stream of reason has not lost its way
> Into the dreary desert sand of dead habit …
> Into that heaven of freedom, my Father,
> let my country awake.

BOX NO. 4.3

HEALTH IMPACT OF PLUTONIUM EXPOSURE

Plutonium emits alpha particles which can be effectively stopped by the skin. Hence, the two primary routes of biological damage by plutonium contamination are ingestion and inhalation. Ingestion of plutonium is a less significant risk since almost all the plutonium is excreted within a few days.[32] A more serious risk comes from the inhalation of very small plutonium particles, which can stay imbedded deep in the lungs typically for periods up to one year, leading to increased rates of lung, liver and bone cancers. This risk is directly proportional to the radiation dose to the body and there appears to be no threshold below which the probability of cancer is zero. The dose from a radioactive substance depends on the kind of radiation it emits, the energy of the emitted radiation, how the substance is distributed within the body, and how long it resides therein.

While plutonium-239 decays primarily through alpha decay, it also emits gamma rays. Therefore, in addition to the internal dose due to inhalation, there could also be an external dose. However, the external dose from standing in a cloud of plutonium aerosol is a factor of 100 million smaller than the inhalation dose (Fetter and von Hippel 1990, 38).

If the skin is punctured or damaged by acid or thermal burns, a significant amount of plutonium can be absorbed into the subcutaneous tissue and blood. Insoluble particles and metal slivers deposited below the level of the epidermis are slowly cleared to regional lymph nodes (BEIR 1988, 307). Investigations involving beagles found that, following a subcutaneous implant of plutonium, a substantial fraction was still present in the body, distributed in the injected region, regional lymph nodes, the liver and the skeleton, several years later (Dagle and Sanders 1984a, 73).

Human epidemiological studies of the effects of plutonium inhalation are limited. Hence, two approaches can be used to estimate the risks. The first involves the use of estimated lifetime risks obtained from laboratory animal experiments. Difficulties with this approach relate to the many differences between animals and humans, including differences in histological types of cancer, differences in confounding exposures (for example, smoking), differences in spontaneous risks, and differences in lifespan. The second approach involves expressing risks obtained from humans exposed to alpha radiation from radon decay products, for which data from epidemiological studies with miners are available, or to low-LET[33] X-ray and gamma radiation in terms of dose (or dose-equivalent) to the lung or other relevant tissues. These risk estimates are then applied to the doses resulting from high-LET alpha radiation from transuranic elements. One difficulty with this approach is that there may be characteristics of specific exposures that are not fully reflected in a single dose estimate but that may affect resulting health-effect risks. Based on these approaches, various radiation standard–setting organizations, such as the International Commission on Radiological Protection (ICRP 1991, 22) and the US National Research Council Committee on the Biological Effects of Ionizing Radiation (BEIR) estimate that each mg of inhaled plutonium increases the risk of cancer, primarily of the lung, bone or liver, by 6 to 12 per cent.[34]

A different set of health effects are associated with the inhalation of comparatively large amounts of plutonium. These are based on experiments with animals and have shown radiation-induced pneumonitis (inflammation of the lung) and fibrosis (scarring of lung tissue) among other end points (Dagle and Sanders 1984b, 129). Death has resulted within a few months in these cases.

5

Heavy Water

If I may say so, this secrecy is intended to screen the inefficiency, waste and perhaps the shady transactions of the AEC.

—N. Sreekantan Nair,[1] Indian Parliament, 10 May 1954

Heavy water is the third key material for the nuclear establishment. The first of the three phases of the programme for atomic energy development in India advocated by Homi Bhabha involved the construction of heavy water reactors. Heavy water is used in these reactors both as moderator (to slow down neutrons emitted during fission so that they have a higher probability of being captured by other fissile nuclei, thereby causing them to fission and keeping the chain reaction going) and as coolant (to carry away the heat produced). Some aspects of the history of heavy water in the country are reminiscent of the larger saga of nuclear power—high in costs, poor in performance and low in accountability.

HISTORY

The scientific understanding of heavy water goes back to a paper from 1932, that crucial year for nuclear physics. The first issue of Volume 39 of *Physical Review*, the leading physics journal, published that year, carried a short two-page note titled ‘A Hydrogen Isotope of Mass 2’ by Harold C. Urey, F.G. Brickwedde and G.M. Murphy in the Letters to the Editor section (Urey, Brickwedde, and Murphy 1932). Unlike normal hydrogen, this isotope of hydrogen contains one proton and one neutron, and it came to be called deuterium. For ‘his discovery of heavy hydrogen’, Urey was to receive the Nobel Prize in Chemistry in 1934 (Nobelprize.org 2009).

Shortly thereafter, Urey, together with Edward Washburn, also prepared the first isotopically-enriched sample of heavy water (HW), water in which both hydrogen atoms have been replaced with deuterium. One difference in nuclear properties because of this replacement—its low neutron absorption compared to normal (or light) water—was noticed in 1937 by Hans von Halban and Otto Frisch (Waltham 2002). By 1939, von Halban, now in collaboration with Frédéric Joliot-Curie and Lew Kowarski, realized that the substance could act as a moderator of neutrons. During the Second World War, Kowarski and von Halban ended up in Montreal, where they worked with Canadian researchers on the design of a heavy water–moderated nuclear reactor for the production of plutonium for use in atomic bombs.

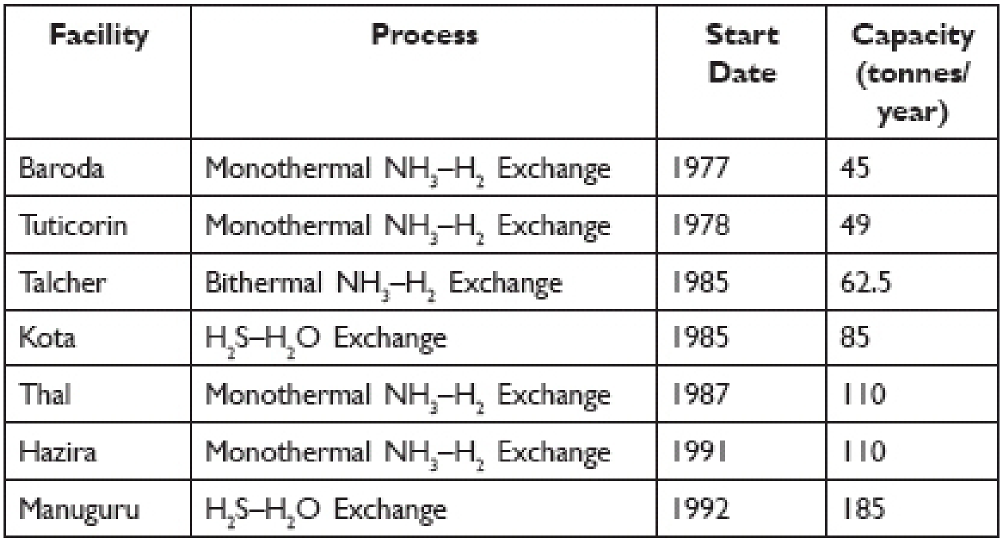
This idea was later adopted in the electricity-generating reactor that was proposed by W.B. Lewis and his colleagues at the Chalk River Laboratories in Canada; in 1954, after considering both regular water (light water) and heavy water, based on economic considerations, they decided on the latter as a coolant as well (AECL 1997, 191–93). It is also possible to use light water or organic fluids as coolant (Nero 1979, 109).

PRODUCTION TECHNOLOGIES

Heavy water is naturally present in ordinary water, but only in small amounts, roughly one part in five thousand or less. For use in reactors, the HW must be concentrated to nearly 100 per cent. There are many ways to do this, but not all of them are practical on an industrial scale. While all these methods involve the expenditure of large amounts of energy, some require even more energy than others and are therefore not pursued.

In India, HW is produced by the Heavy Water Board (HWB), an industrial unit of the DAE that was set up in 1989. Its precursor, Heavy Water Projects, had been set up in 1969. HWB's plants operating in the country are based on two different processes: the hydrogen sulphide–water exchange process and the ammonia–hydrogen exchange process.[2]

TABLE 5.1: HEAVY WATER PRODUCTION FACILITIES



Facility	Process	Start Date	Capacity (tonnes/ year)
Baroda	Monothermal NH_3–H_2 Exchange	1977	45
Tuticorin	Monothermal NH_3–H_2 Exchange	1978	49
Talcher	Bithermal NH_3–H_2 Exchange	1985	62.5
Kota	H_2S–H_2O Exchange	1985	85
Thal	Monothermal NH_3–H_2 Exchange	1987	110
Hazira	Monothermal NH_3–H_2 Exchange	1991	110
Manuguru	H_2S–H_2O Exchange	1992	185

A variant of the ammonia–hydrogen exchange process is used in the Talcher plant. The Talcher plant's operations seem to have been suspended since 1994; in the last few years, facilities to produce various organic solvents used in the nuclear fuel chain have been set up there.

PRODUCTION PROBLEMS

Historically, the DAE has struggled with heavy water production. Despite deciding in the 1950s on heavy water reactors as the predominant reactor type for the first phase of its nuclear programme, the DAE did not manage to produce sufficient quantities of HW for several decades. There were substantial delays in commissioning HWPs; once commissioned, they suffered frequent failures. Further, the quality of the HW produced was also reportedly poor in quality (low grade) and not usable in reactors (Manchanda 1989, 18).

The Parliament's Estimates Committee has repeatedly criticized the DAE's failure to produce adequate quantities of heavy water. In its 1969–70 report, for example, the committee said, 'nothing substantial has been done in the matter' of producing the HW required for the Rajasthan and the Madras Atomic Power Stations. The concern was repeated in its 1972–73 report and yet again in its 1977–78 report (Mirchandani and Namboodiri 1981, 58–59).

More than a decade later, the 1989 Public Accounts Committee report to the Lok Sabha was caustic in its evaluation (quoted in Public Accounts

Committee [1991–92] 1992, 11):

> The Committee regret to observe that the Department of Atomic Energy could not ensure timely supply of requisite quantity of heavy water to both units of Madras Atomic Power Project. The commissioning of the first unit alone was delayed by more than 16 months due to non-availability of heavy water which according to audit, meant an estimated revenue loss of the order of Rs 56.42 Crores. Considering the fact that the Madras Atomic Power Project was already running behind the [*sic*] schedule, the non-availability of heavy water at appropriate time shows nothing but *another facet of poor planning* in the Department of Atomic Energy. (Our emphasis)

All these delays resulted in the DAE's having to import HW from the Soviet Union for the Rajasthan Atomic Power Station in 1976 (Tomar 1980, 528). The heavy water was under IAEA safeguards.[3] During the 1980s, there were also several allegations, persuasively argued but because of the nature of the transactions never fully substantiated, that India had imported HW through clandestine means (Milhollin 1986). In particular, there was some evidence that some HW from Norway had been diverted to India through Romania (Gordon 1990; Hazarika 1989). Since the DAE has never been transparent about the functioning of its HWPs, it is not easy to evaluate these allegations.

It was only in the early 1990s that HW ceased to be such a bottleneck. This was partly because five HWPs were commissioned in the late 1980s and the early 1990s. But equally important was the failure to meet with the planned pace of commissioning reactors leading to a decrease in the demand. This was the reason for exporting heavy water in the last decade, albeit in quantities that are small compared to the initial load needed by a reactor to start operating.

PERFORMANCE

The few publicly available pieces of information suggest that many HWPs have been shut down for relatively extended periods of time even after commencement. These records are almost necessarily incomplete and only give us an 'upper bound' on the performance of the HWPs; that is, it is quite possible that they have had more shutdowns than we know of. Further, the periods reported for the outages underestimate the actual loss of time because there is typically a substantial period after each restart (following an outage) when the HW produced is not of adequate quality.

The plants that seem to have been particularly poor performers are Baroda and Tuticorin. As mentioned earlier, Talcher appears to have been shut down since 1994. The HWP in Baroda was to be commissioned in January 1973, but it became operational in July 1977, and actual production started only in November 1977 (CAG 1988). Within ten days, it was shut down because of mechanical failures, a major explosion and a hydrogen fire causing extensive damage to the plant. It took nearly three years for the plant to restart production. Since then the production has been frequently interrupted by disruptions in power or problems with the associated fertilizer plant (M.R. Srinivasan 2002, 222).

Reported outputs for the first three years of production after restarting were far below the design capacity of 45 tonnes/year: 12 tonnes in 1981, 5 tonnes in the fiscal year 1982–83 and 13.6 tonnes in the fiscal year 1983–84 (Milhollin 1986, 164). According to CAG, the average annual production for the 'seven years 3 months up to 1987 was less than 30 per cent of the installed capacity' (CAG 1988). There is little public information available since then about production levels at Baroda.

In 1998–99, the operation of the Baroda plant was suspended 'owing to change of operating technology at the fertilizer plant to which the HWP is linked' (Standing Committee on Energy 2000, 10). The DAE began implementing a Baroda Revival Project, which was expected to be completed by the end of 2002 (DAE 2002b, 36). In July 2004, the newly constructed ammonia-water-exchange technology unit was 'dedicated to the nation' (*India Business Insight* 2004).

The new plant evidently developed snags and the 2005–06 annual report of the DAE described the 'restart of the plant in September 2005, after addressing comprehensively and rectification [*sic*] of the corrosion problem of Front End columns of 70 C1/C2'; it was only on 30 December 2005 that the plant managed 100 days of continuous operation (DAE 2006a, 28). But, in May 2006, there was a major leak of ammonia and a plant emergency was declared (AERB 2007, 20). The DAE's annual report makes no mention of this accident. The official history of the AERB mentions that it 'granted the licence for operation of HWP–Baroda in June 2006' (Sundararajan, Parthasarathy, and Sinha 2008, 80). In the 2009–10 annual report of the DAE, the Baroda HWP was described as a 'technology demonstration plant', suggesting that it was not intended for industrial-level production (DAE 2010, 34).

The Tuticorin HWP, too, has a history of poor performance. In 1988, the Comptroller and Auditor General reported that the plant had an annual average production of 14.6 tonnes, in comparison to an achievable capacity of 49 tonnes (Public Accounts Committee [1992–93] 1993, 23). CAG also found that 'running costs were high' and that the 'manpower employed was about 13 times more than that envisaged in the project report' (Chandrasekharan 1990, 1028–29). More recent reports suggest that, throughout its operating history, production of HW at Tuticorin has suffered from frequent interruptions of power and the low load operation of the fertilizer plant (M.R. Srinivasan 2002, 223; DAE 2003a, 5). It was also shut down for over four months in 1995–96 due to the failure of a heater coil (DAE 1996a, 16). In 1997–98, it was shut down for one and a half months when the ammonia plant was shut down (DAE 1998a, 3–8). The plant was shut down for ninety-four days during 2001–02 (Standing Committee on Energy 2003b, 41). In 2007–08, it was again shut down because of 'non-availability of synthetic gas supply from SPIC' (AERB 2008, 20). The problem proved persistent and the DAE's 2009–10 annual report reported that the plant is 'presently kept in preservation under nitrogen atmosphere' (DAE 2010, 37), and this continued in 2010–11 (DAE 2011, 54).

Other plants, too, have had extended outages. Again, because the available information is so sparse, it is possible that there may have been other outages as well. The Kota plant was shut down from September 1986 to February 1987 (DAE 1988, 10). It suffered from prolonged outages in 1997–98 (DAE 1999, 20), including for five months from June 1997 (DAE 1998a, 3–8). In 2003–04, its performance suffered due to frequent outages of the RAPS II reactor (Parliamentary Standing Committee on Science & Technology, Environment & Forests 2004, para 25).

In 1989–90, the Thal plant had an extended shutdown of one production stream, a total plant shut down due to a heavy monsoon, and a reduced supply of feed synthesis gas from the fertilizer plant (DAE 1991b, 11). It suffered extended outages again in 1998–99 (DAE 2000a, 24). In 2001–02, the Thal plant was shut down at least twenty-two times (Standing Committee on Energy 2003b, 41).

Though it began operations in 1991–92, the Manuguru plant achieved ‘design capacity’ only in 1995–96 (DAE 1996a, 16). Since then, it has had outages due to poor supply of coal and of hydrochloric acid (DAE 1997a, 3:8). It was shut down from 12 February to 5 March 2002 on account of a strike by workers (Standing Committee on Energy 2003b).

For many years, the Hazira plant has been described as producing heavy water ‘under reduced load’ due to retrofitting of one of the two ammonia units of the fertilizer plant to which it is linked, or to restricted natural gas supply from the Gas Authority of India.[4] It also had prolonged outages in 1997–98 (DAE 1999, 20), and was down for eighty-five days during 2000–01 (Standing Committee on Energy 2003b, 40). In August 2006, the Hazira plant was shut down on account of heavy rain and floods (*Business Line* 2006).

There are a couple of scattered reports of combined HW production at the DAE plants. The total annual yield of all the six operating HW plants as of 1987 was reported to be ‘no more than 190 tonnes’ (Bhargava 1992, 740). The corresponding figure from 1992 was 273 tonnes (Fernandez 1992). Both figures imply an average capacity factor of about 50 per cent.

Going by the DAE’s and the HWB’s publicity documents, the performance of HWPs seems to have improved (*Nuclear India* 2002a). But, since the earlier performance was dismal, *improved* performance by itself does not mean a lot. Likewise, reports of lowered energy consumption and water consumption (see, for example, Hiremath 2004) though commendable, do imply that the initial designs of HWPs and their operations were relatively wasteful in their use of energy and water.

One can estimate how well HWPs have performed by estimating the demand for heavy water by the various reactors in the country. The demand arises from new nuclear reactors—which need HW for their initial inventory—and replacement for routine losses of HW. For the period from 1992 to 2006, including the amount of heavy water exported, the total demand would be 3668 tonnes (Ramana 2007a, 3486). Since then, three new 220-MW reactors (Kaiga IV, RAPS V and VI) have been commissioned and about thirty-three tonnes of heavy water has been exported. On average, the annual demand for the period from 1992 to 2011 would be about 250 tonnes. The combined capacity of all HWPs except

Talcher (from Table 5.1) is 584 tonnes/year. Clearly the production capacity exceeds the demand and the necessary minimum capacity factor from 1992 to 2011 is a mere 42 per cent. Including the Talcher plant, which could be justified because of the expenses incurred in constructing it, would bring this down to about 39 per cent.

Excess capacity is a peculiar problem. If the DAE were to run its HWPs at high capacity factors—assuming that the DAE's claims about improved performance are true and that there are no technical problems—then, the production would exceed the demand. There is at best a limited export market for HW since very few countries operate heavy water reactors. Thus, production at high capacity factors would only lead to surplus accumulation with increased operating cost, but no corresponding revenue. The alternative to this scenario is to run the HWPs at lower capacity factors—around 40 per cent going by the estimates above.

DUBIOUS ACCOUNTING

The DAE has tried hard to prevent appreciation of the full implications of the poor performance of its heavy water plants. For example, when CAG examined the cost of the Baroda HWP, the DAE 'did not produce to Audit either the actual production of heavy water or the cost of production' (CAG 1988). CAG also found evidence of poor accounting practices, such as not including actual expenditure on maintenance and spares. CAG's estimate of the cost of production at the Baroda HWP was 'in excess of Rs 6886 per kg as against the projected cost of Rs 478 per kg and revised cost of Rs 1023 per kg' (Chandrasekharan 1990, 1032).

A few years later, CAG noted that the DAE had not prepared the pro-forma accounts for the years after 1982–83 though they were prepared till that year (CAG 1992). The Parliamentary Public Accounts Committee considered this refusal of the DAE to provide accounts and production details as yet 'another instance of lack of proper accounting procedure which in turn is due to their disregard of accountability on their part. The Committee strongly deprecate such attitude' (Public Accounts Committee [1992–93] 1993, 2). In its response, the DAE stated that 'Heavy Water being strategic material, it is not advisable to divulge information relating to its production and cost to functionaries at all levels.' The committee did not agree with this and maintained that ‘as already recommended pro-forma accounts will have to be compiled … the Committee do not understand how preparation thereof will result in release of any sensitive data. The Committee consider such claim as a way of evading accountability by escaping scrutiny of audit and this Committee under the guise of sensitivity, public interest etc.’ More than a year after the Public Accounts Committee tabled its report in Parliament, CAG complained that the ‘pro-forma accounts of Heavy Water Pool Management for the years 1982–83 onwards have not been sent for audit so far despite this fact being mentioned in successive Reports of the Comptroller and Auditor General of India: Union Government (Scientific Departments) since 1987’(CAG 1994).

In August 1998, finally, the Heavy Water Board ‘made available the pro-forma accounts for the period 1993–94 to 1996–97 … for audit certification.’ But then, what CAG found, perhaps not surprisingly, was ‘that the cost of production of heavy water had been reckoned at a rate lower than the actual cost’ (CAG 2005, 21). This resulted in DAE’s charging Rs 1.3 billion less from NPCIL during 1993–98 compared to what it may have recovered at the ‘correct’ prices. Even then, the DAE continued to not charge appropriately for HW and in March 2006 stated that this was necessary to ‘make nuclear power competitive with other forms of energy’ but the CAG refused to accept this logic (CAG 2006, 131).

COSTING HEAVY WATER

The cost of heavy water became a crucial factor in the debate over the economics of nuclear power around 2005–07 (see [5] The lease rate is based on an HW price of Rs 12,525/kg (2003 prices) (S. Thakur 2005, 5209). As a part of the debate with NPCIL, I showed that the price charged for HW does not actually reflect the full cost of production (Ramana 2007a).

It is not possible to definitively estimate the cost of heavy water production for the simple reason that there are no public figures available for the amounts of HW produced at heavy water plants on a consistent year-by-year basis.[6] The annual reports and performance budgets of the DAE list, for example, the annual electricity production at various reactors; however, they conspicuously avoid giving any numbers for HW production. The same is true of the many Internet websites of the DAE and its associated organizations. At best, what is seen in DAE documents are statements like ‘target met’, without any indication of what the target is. But, as discussed above, we can put a limit on what optimized production should have been by looking at the demand.

I used two methods to estimate the heavy water cost. The first method amortizes the capital costs into an average annual capital cost and this amount is added to the average annual operations and maintenance (O&M) and fuel costs. These costs are divided by the average annual production to get an estimate of the cost of HW. The second method calculates a levelized cost, which is the ratio of the present values of the life-cycle cost of producing HW and the annual amounts of HW produced over the lifetime of the plant. In either case, at a 60 per cent capacity factor, well above the necessary efficiency (averaged over all plants) to meet with the demand, the cost of heavy water turns out to be about Rs 24,000 per kg of heavy water, twice or more the price at which the DAE sells heavy water to NPCIL. Even at an impossible 100 per cent capacity factor, the cost of production turns out to be higher than the DAE’s cost of supply to NPCIL. This proved something that many had conjectured over the decades: that the DAE subsidizes the NPCIL by providing cheap heavy water. For example, Muralidharan (1988) has argued that ‘in addition to cheap finance, the nuclear power programme enjoys, *in all probability*, another *implicit subsidy in the form of the cost and lease rate borne for its heavy water supplies*’ (192) (our emphasis). My results showed that, as per standard and required accounting practices, a subsidy of over Rs 12,000 per kg of HW was, and is, being offered. Since hundreds of tonnes of the substance are required to even start operating a new reactor, the total cost of subsidy could be considerable.

6

Economics

> *Nuclear power, which early advocates thought would be 'too cheap to meter', is more likely to be remembered as too costly to matter.* [1]
>
> —*The Economist* 2001

Making nuclear power seem cheap has been understandably important to the DAE. In a developing country like India that had just become independent, there were numerous demands on scarce government finances. It would have been difficult to garner the large amounts of public funding needed for the nuclear programme if those running the programme, like Bhabha, were to be honest in estimating the actual cost of nuclear power, or even be open about the uncertainties involved in assessing it. Hence, almost from the very inception of the nuclear programme, the DAE has confidently asserted that nuclear power was economical.[2] Today, more than half a century later, the assertion that nuclear power is cheap continues to be important in persuading policymakers to invest in expensive reactors, reprocessing plants, uranium mines and a host of other facilities.

But, in reality, nuclear power is anything but cheap. As an influential interdisciplinary study conducted at the Massachusetts Institute of Technology some years ago baldly stated, 'Today, nuclear power is not an economically competitive choice' (Deutch et al. 2003, 3). The lack of competitiveness arises mainly from its capital-intensive nature. The ongoing electricity sector restructuring process around the world, leading to a greater emphasis on economic competition, has accentuated this problem. Financial risks that were previously borne by consumers are increasingly seen as the responsibility of investors.[3] The increasing role of economic markets in electricity supply has also brought with it greater demands to curtail subsidies or at least to make them explicit and subject to democratic debate (*Economist* 2001). The nuclear industry, in India as elsewhere, has tried to resist such efforts, albeit with varying degrees of success.

This chapter examines the economics of nuclear power. It begins with an overview of efforts by early advocates of atomic energy, primarily in the United States, to promote the idea that nuclear power was cheap. This is followed by a summary of the DAE's assertions about the economics of nuclear power and some attempts by independent analysts to examine them. After outlining one of the standard methodologies of energy economics, the cost of generating electricity at the Kaiga Atomic Power Station and the Raichur Thermal Power Station (VII plant) are compared.[4] The analysis laid out demonstrates that, for realistic choices of various economic parameters, nuclear power from PHWRs is more expensive than thermal power. Also discussed in detail is the relative economics of the prototype fast breeder reactor and the DAE's proposed 700-MW PHWRs. Unlike what the DAE maintains, electricity from the PFBR will be significantly more costly than from PHWRs.

What does this mean for the nuclear establishment's plans of rapidly expanding the contribution of nuclear energy in the nation's electricity sector? The answer is simple. It would result in the overall supply of electricity becoming more high priced. This would be exacerbated by the DAE's plans for including a large fraction of breeder reactor capacity. For a country that already has high electricity rates—industrial tariffs are among the highest in the world (Rao, Sant, and Rajan 2009)—nuclear energy remains, as commentator Sukumar Muralidharan (1985, 109) pointed out a quarter century ago, 'an expensive indulgence'.

PROMISE AND UNCERTAINTY

Arguably the most notorious statement in the history of nuclear power was the prognosis that it would be 'too cheap to meter' the electricity produced in reactors. This prediction was, ironically, not that of someone trained as a physicist, an engineer or an economist, but someone who never went to college, who started his career as a travelling shoe salesman. Lewis L. Strauss rose from his first position to become a partner in a Wall Street investment bank and, eventually, chairman of the United States Atomic Energy Commission (USAEC) (Pfaul 1984).

During his term as chairman of the USAEC, Strauss was directed by US President Dwight Eisenhower to come up with a proposal to reach out to the world with peaceful nuclear power, and steer global attention away from atomic weapons. The results were on display on 8 December 1953, when, at the United Nations General Assembly presided over by Vijaya Lakshmi Pandit, Nehru's sister, Eisenhower gave his famous Atoms for Peace speech. Delivered at a time when the nuclear arms race between the United States and the Soviet Union was causing alarm around the world, Eisenhower's primary aim was to play up the United States as both leading the effort to contain the arms race and trying to harness the atom for global development.

The United States, he said, 'knows that if the fearful trend of atomic military build-up can be reversed, this greatest of destructive forces can be developed into a great boon, for the benefit of all mankind'. The sales pitch that Eisenhower laid out promised much, especially to those countries that used to be called 'underdeveloped' in that era.[5] 'Experts would be mobilized to apply atomic energy to the needs of agriculture, medicine, and other peaceful activities. A special purpose would be to provide *abundant* electrical energy in the *power-starved areas of the world*' (our emphasis). The motif of abundance was to figure frequently in descriptions of nuclear power.[6]

The speech was a shot in the arm for the nascent nuclear industry. Within the next year, the USAEC 'would announce a programme of incentives to encourage American utilities to build nuclear reactors; at the same time, it began developing plans for assisting other countries with new nuclear programmes' (Cooke 2009, 110). These plans were systematically advertised (Pringle and Spigelman 1981, 122). Following Eisenhower's address to the United Nations, his aides produced a pamphlet containing the speech in ten languages. Within two weeks, over 200,000 copies were sent by US firms in their foreign mail. Newspapers and radio and TV stations were given briefings, articles and special advertising.

As chairman of the USAEC, Strauss was a leader in furthering the propaganda about how nuclear power was to change the world. Nine months after Eisenhower's speech, Strauss prophesied to the National Association of Science Writers in New York, 'It is not too much to expect that our children will enjoy in their homes electrical energy too cheap to meter, will know of great periodic regional famines in the world only as matters of history, will travel effortlessly over the seas and under them and through the air with a minimum of danger and at great speeds, and will experience a lifespan far longer than ours as disease yields and man comes to understand what causes him to age.' The following morning, on 17 September 1954, the *New York Times*, as influential then as it is now, carried a report on the speech, beginning the countless repetitions of this forecast.

Although 'visionaries' in a number of countries were prophesying cheap nuclear power, it was Strauss's 'too cheap to meter' that really captured the imagination of people around the world and provided a catchy jingle to help sell the merits of nuclear power. Decades later, DAE officials, like P.K. Iyengar, continued to maintain their commitment to Strauss's dream, saying 'there will be no need to meter electricity distribution'; he also bemoaned the incorporation of 'additional safety devices' that 'increased the capital cost of nuclear power beyond that of any fossil fuel source' (Iyengar 1999, 70).

Even as Strauss and other prophets were extolling how cheap nuclear power would be, within the United States itself, many who were in the business of actually building power plants were convinced that nuclear power would be anything but cheap. As C.G. Suits, vice-president and director of research at General Electric, told the American Association for the Advancement of Science in December 1950, 'At present, atomic power presents an exceptionally costly and inconvenient means of obtaining energy which can be extracted more economically from conventional fuels … The economics of atomic power are not attractive at present, nor are they likely to be for a long time in the future. This is expensive power, not cheap power as the public has been led to believe' (Makhijani and Saleska 1999, 63).

Others highlighted the uncertainties inherent in predicting costs at such an early stage in the process. Philip Sporn, president of the American Gas and Electric Company and chairman of the Advisory Committee on Cooperation between the Electric Power Industry and USAEC, explained:

‘Since almost no facts are available from which to determine with any degree of accuracy what the cost of such a power plant will be, it is obvious that the foundation of the discussion [on the economics of atomic energy] is not very solid’ (Sporn 1950, 303). Therefore, Sporn pointed out: ‘estimates must be largely guesswork because we lack the essential facts for accurate engineering judgment’. Another Yale University academic opined: ‘What it will cost to produce atomic energy for industry is at best an informed guess, and the average of nine, or ninety, guesses is still a guess’ (Jones 1951, 268).

The situation today, even after over 400 power reactors have been built, is not very different. There is still enormous uncertainty in how much it would cost to build a new nuclear reactor and how long it would take.[7] In the United States, estimates of the cost of nuclear power made between 2001 and 2009 have varied by over a factor of six (Cooper 2009, 23). What is different from the early 1950s is the realization, in the light of cost overruns in practically every country that has built reactors, that the low estimates of reactor construction costs are unlikely to materialize.

MOVING TARGETS

As early as 1958, barely a few years after the DAE was set up, Bhabha stated ‘even at costs based on present technology, nuclear power would become cheaper in capital investment and in cost of electricity than coal power in most parts of India within ten years’ (Bhabha and Prasad 1958, 100). The ‘most parts of India’ referred to regions away from coal mines. The higher cost of transporting coal to such areas over ‘hundreds of miles’ would, Bhabha claimed elsewhere, make nuclear power more competitive (Jain 1974, 22).[8]

Bhabha’s comparison of nuclear power with coal was based on ‘information supplied by various industrial consortia in the United Kingdom’ but made allowance ‘for lowering civil engineering and labour costs in India and the higher cost of those items of equipment, which may have to be imported from abroad at the initial stages”’ (Bhabha and Prasad 1958, 95). On the basis of this argument, Bhabha assumed that a nuclear reactor would cost Rs 1700 for each kilowatt (kW) of electricity-generating capacity, as compared to Rs 1050/kW for a coal-powered thermal plant—

higher, but not reflective of what the actual construction costs of nuclear reactors were to be.

Around the same time, and perhaps based on similar data, the United Kingdom also had come out with a White Paper entitled *A Programme of Nuclear Power* which estimated that the cost of electricity from nuclear reactors would be approximately the same as the generating cost of contemporary coal stations (Williams 1980).[9] The UK effort to make the economic case for nuclear power over coal was motivated in part because political leaders wanted to weaken the 'powerful coal interests in the grip of left-leaning miners' unions, feared and hated by the establishment' (Cooke 2009, 138).[10] As a result, economists working for the government were told to rework the numbers using various tricks to make nuclear power look competitive. An important trick was to assign a value to plutonium ('the plutonium credit'), predicated on the belief that a large demand for plutonium would emerge in the future (Walker 1999, 9; Cooke 2009, 138).

In addition to underestimating construction costs, Bhabha also made a number of other assumptions that were favourable to nuclear power, in particular, that the operating costs of a nuclear reactor would be the same as those at thermal power stations, and that the cost of mining uranium and fabricating it into fuel would cost Rs 300 to Rs 400 per kg.[11] Despite this leeway with his cost assumptions, the cost of nuclear power turned out to be about 5 per cent more expensive than both coal- and oil-based thermal power. This is where the plutonium credit idea pioneered by the British nuclear establishment came in. To make nuclear power seem competitive, Bhabha assigned an arbitrary credit of Rs 56,000 for each kilogram of plutonium produced in the nuclear reactor.[12] Then, the per kilowatt-hour costs came out to be Rs 0.04050, Rs 0.03910 and Rs 0.03907 for coal, oil and nuclear power respectively. The jugglery with the plutonium credit made nuclear power just that little bit cheaper.

There was no justification for this arbitrary choice of the plutonium credit even then. In hindsight, however, it has become clear that the extraction and storage of plutonium is so expensive that it should be considered a liability. Its appearance in a nuclear utility's accounting books should be in the debit column, not the credit column.

Bhabha's claims about the economics of nuclear power were soundly rebutted by at least a couple of economists. One of the most significant British contributors to welfare and development economics, I.M.D. Little, 'was not very impressed with the fact that the low end of Bhabha's range of atomic energy costs almost exactly coincided with the costs of conventional energy' (Wohlstetter 1977, 3–44). Little observed that this was also the case with the British White Paper and speculated that such a result 'suggests a bias on the part of the estimators who may feel bound to get their estimates for nuclear energy down to the level of conventional energy' (Little 1958, 1483). He was also sceptical of Bhabha's assumed capital cost for a nuclear reactor. He pointed out that 'the cost per kW in England for a conventional station is now estimated to be only … Rs 666,' as compared to the Rs 1050 that Bhabha had assumed. He then went on to argue, 'I am quite prepared to believe that the actual cost [of a coal plant in Bombay] would work out to be higher than in England. But I would like to know why the nuclear plant would also not work out at more than in England' (1483).

Little used cost, performance and financial parameters that were more representative of the technologies of the day to find that nuclear power would cost 50 to 60 per cent more than thermal power. Another prominent economist from the Massachusetts Institute of Technology, Paul Narcyz Rosenstein-Rodan, was trenchant about Bhabha's idea that, because of the shortage of electricity in India, the nation should embark on an ambitious and expensive nuclear programme, saying, 'When a man is hungry he may pay a high price for a meal, but he should not proceed to buy a restaurant' (Rosenstein-Rodan 1959, 11).

There is no evidence that these critical assessments received much notice in Indian policymaking circles. The 1965 'Report of the Energy Survey of India Committee', for example, stated: 'In areas where coal must bear a high transport cost, and hydel is not available, there is clearly likely to be scope even at present costs of nuclear energy … The longer term place of nuclear energy in the Indian energy economy must wait the development of economic methods for using thorium. We may hope that these methods may be available by the 1970s' (ESC 1965, 132). The hope about thorium was optimistic in the extreme. There are still no cost-effective methods for using thorium, and none are likely to come up for some more decades at the very least, if ever.[13]

In defence of the Energy Survey of India Committee, it must be said that they did carry out calculations of relative costs of coal, hydel and nuclear power for different parameters. But these were based on assuming a total investment per kilowatt of capacity of Rs 1904 for a CANDU-type reactor (ESC 1965, 130–31). No sources for this figure are given, but one might expect that the presence of M.N. Chakravarti from the Department of Atomic Energy on the committee, and H.J. Bhabha, Secretary and chairman of the Atomic Energy Commission, in the list of advisers to the committee (ESC 1965, 3), may have had something to do with it.[14] The first, and cheapest, CANDU reactor built in India, RAPS I, cost somewhere between 25 per cent to 150 per cent more than this estimate, after accounting for inflation, depending on what is taken as the power rating of the reactor because of its variations over the years.

The Energy Survey Committee at least tried its hand at calculating the cost of nuclear generation. But even this cursory level of interest in costing nuclear power is not to be found in the 1974 ‘Report of the Fuel Policy Committee’ or the 1979 ‘Report of the Working Group on Energy Policy’. Neither of them considered the unfavourable economics of nuclear power when recommending that it be expanded on a vast scale. In the former’s assessment, the ‘capacity of nuclear power stations could be … 4600 MW’ by 1990–91, but the committee emphasized that it ‘w*ould like to endorse the view of the DAE that nuclear power capacity, if possible, should be increased to the maximum extent possible by 1990–91*’ (FPC 1974, 83) (emphasis in original). Likewise, the latter concluded that an ‘installed nuclear capacity of 5000 MWe has been visualised by the year 2000–01 considering the present constraints’, but recommended evolving ‘measures to accelerate the nuclear power development to achieve an installed capacity of 8000–10,000 MWe by the turn of the century’ (WGEP 1979, 70).

BOX 6.1:

ALTERNATIVE ESTIMATES

During the early 1980s, independent researchers outside the DAE started examining the economics of nuclear power. Writing in that unique journal, the *Economic and Political Weekly*, Deb Kumar Bose took on the DAE's claim about the comparative economics of nuclear and thermal power (D.K. Bose 1981). Bose had evidently come across a 1977 paper by AEC Chairman Homi Sethna and future AEC chairman M.R. Srinivasan in the proceedings of a meeting of the International Atomic Energy Agency that mentioned some capital cost figures for the DAE's nuclear reactors. Bose used those, as well as data on coal plants that Bharat Heavy Electricals (BHEL) had supplied, to estimate that nuclear power was 17 to 20 per cent more expensive than coal power, depending on the efficiency of the plant (D.K. Bose 1981, 1314).

Another outsider who compared the costs of nuclear power with those of other sources was Amulya Reddy, a physical chemist who turned his attention to energy and rural development issues in the 1970s. Through his work on supplying energy at the village level, Reddy developed a new approach towards thinking about energy. The basic insight motivating this approach was that electricity itself has no use value; what really count are the services it provides. This includes, for example, illumination, high temperatures for cooking, and pumping of water for irrigation. If these services can be delivered using alternate technologies or devices that consume less electricity, then, the costs involved in such replacements should be considered on an equal footing with the costs involved in expanding supply. Should the demand reduction measures be cheaper, then they should be preferred to investing in expanding electricity generation. Further, amongst the different options for either demand reduction or electricity generation, the cheapest ones should be given preference. Similar ideas were expressed by other energy analysts too (see, for example, Cavanagh 1986; NARUC 1988). But what distinguished Reddy's work was its emphasis on using electricity as a tool for development. Accordingly, he and his collaborators emphasized the importance of electrification of all homes so as to supply good-quality lighting, and an emphasis on shifting to industries that generated more employment per unit of energy consumed. Reddy christened this approach DEFENDUS, for development-focused, end use-oriented and service-directed.

Starting in 1986, Reddy and his colleagues constructed a comprehensive DEFENDUS energy scenario for the state of Karnataka (A.K.N. Reddy 2002, 38). As part of this, they performed a comparative costing of fifteen technologies of electricity saving, decentralized generation, and conventional centralized generation of electricity (Reddy et al. 1990). It turned out that nuclear power was the most expensive of all these technologies. Further, Reddy and his collaborators pointed out that the DAE had used a very low cost for heavy water, Rs 4747/kg at 1986 prices, whereas the Comptroller and Auditor General had estimated a much higher price, Rs 16,906/kg at 1986 prices.[15]

Reddy presented his comparison of the costs of electricity from heavy water reactors and other options for meeting energy needs at the National Workshop on Nuclear Power organized at the Indian Institute of Science, Bangalore, in December 1988. Reddy argued that the proponents of nuclear power claim that 'it is safe, cheap, appropriate, and modern; but the popular meaning of the resulting acronym SCAM is a better description' of what the enterprise actually amounts to (A.K.N. Reddy 2002, 38). The meeting was part of a debate about whether a reactor should be constructed in Kaiga (see chapter 2). As with many other debates in India, unfortunately, Reddy's demonstration that the Kaiga power station would be an expensive way to meet energy needs proved irrelevant in the face of political power: the reactors were constructed.

In 1983, the DAE set up an internal Committee for the Pricing of Nuclear Power which did a comparison of the costs of power at the MAPS I reactor and the Singrauli thermal power station (J.C. Shah 1985). Not surprisingly, the committee adopted various assumptions that were conducive to demonstrating the cost competitiveness of nuclear power.[16] At Rs 5060/kW, the capital cost of the Singrauli power plant, on the other hand, was not only higher than the cost of most coal plants in the country, it was even higher than the assumed capital cost of Rs 4930/kW for the nuclear reactor (J.C. Shah 1985, 364). That was completely at odds with experience all over the world, including India, where capital costs of nuclear reactors have been much higher than those of coal plants. And last but not least, the DAE had to assume that reactors could be constructed much faster than it had done till that point. Based on these favourable, if unrealistic, choices, the DAE arrived at the conclusion that nuclear power compared 'quite favourably with coal-fired stations located 800 km away from the pithead'. And, based on further assumptions about how nuclear-related costs would reduce relative to coal-related costs, it argued that nuclear power 'in the 1990s would be even cheaper than coal-fired stations at pithead' (M.R. Srinivasan 1985, 17).

But, come the 1990s, all that the DAE could claim was that the 'cost of nuclear electricity generation in India remains competitive with thermal [electricity] for plants located about 1200 km away from coal pit head, when full credit is given to long term operating cost especially in respect of fuel prices' (Nema 1999). The increase in distance from 800 km to 1200 km meant that the transportation cost for coal would go up by nearly 50 per cent (CEA 2004, Appendix I). But, like many other claims proffered by the DAE, this claim does not hold up to empirical scrutiny. The two cost comparisons described below—the first, comparing PHWRs with a coal-based thermal plant and the second, comparing the prototype fast breeder reactor with a PHWR—illustrate this point.

CALCULATING COSTS

Claims about competitiveness ultimately revolve around the cost of producing one kWh (or one unit) of electrical energy using different technologies. As detailed in the earlier section, the DAE has usually tried to compare nuclear power with coal-based thermal power. Such calculations are by no means straightforward. For any of these technologies, there are a number of separate cost elements that have to be calculated in order to estimate the overall cost. The chief components of the busbar cost,[17] that is, not including the costs involved in the transmission and distribution of the electricity generated, are: the capital cost of constructing the generating facility, the annual operations and maintenance costs, the fuelling cost and the waste-management expenses required to run the facility in a manner that is in accordance with environmental regulations. One other component in the case of nuclear power is that of decommissioning the reactors after they have been shut down.

The next complication is that these different costs do not all occur at the same time, but over decades. Even the capital cost of the generating facility is incurred over a long period of time. The expenditures start with activities that have to be carried out before construction commences, including, but not limited to, site selection, project report preparation, preparation of environmental impact assessment, and placing orders for components that could take a long time to manufacture. Construction of the facility could take years, sometime decades. There will also be expenses involved after construction is completed, for example, loading the reactor with fuel or heavy water.

The products of the generation facility, namely units of electrical energy, are also produced over decades. The amount of electricity produced could vary over the years because the facility may be shut down for long periods at times, for instance, to carry out maintenance procedures. Thus, the revenue generated by a facility will vary from year to year. It is customary to average out these variations and talk about a lifetime capacity or load factor.[18]

BOX 6.2:
THE PROBLEM WITH COMPARING TARIFFS

Whenever the issue of the economics of atomic energy comes up, the nuclear establishment likes to claim that its tariffs are competitive with thermal power. For example, the 2007–08 annual report of the Nuclear Power Corporation announced: ‘nuclear power tariffs are currently competitive with those of thermal power plants located away from coal pitheads. The tariff of one station, TAPS, is 94 paise/kWh and that of three stations, MAPS, NAPS, KAPS, below Rs 2. In the year 2007–08 the average tariff of NPCIL power stations was Rs 2.28' (NPCIL 2008a, 49). Compare this with the Mundra power project in Gujarat that is to use imported coal and whose tariff of Rs 2.26/kWh was arrived at through a process of competitive bidding. It seems as though nuclear power is indeed competitive. But there are problems with such a comparison.

One of the problems has to do with the selective choice of reactors by NPCIL—the ones that were commissioned more than a dozen years earlier. In older reactors, much of the capital cost—the most significant component of the electricity cost—would have been 'amortized' or paid off. Thus, the tariff would primarily reflect the expenses involved in fuelling and O&M. If one were to compare a new nuclear reactor with coal plants, old or new, the picture would be quite different. Such differences between tariffs of old and new facilities are also seen in the case of hydropower dams where, again, the capital cost is the primary determinant of the tariff. This is the main reason why generating electricity at the old Bhakra-Nangal project cost Rs 0.135/kWh whereas the same at Tehri station I is Rs 3.50 (CEA 2008). This dependence on time is avoided by comparing levelized costs rather than tariffs.

The more important drawback in comparing tariffs is that the calculation procedure ignores the time value of money and the gestation period of the project. For example, the total capital cost of the project is calculated by adding up expenditure figures from various years.[19] This means that a project which takes many years to build and generate electricity would appear equivalent to one which delivers power in a shorter time but with the same total investment.

There are further problems with nuclear power tariffs. Unlike other sources of electricity—whose tariffs are set by a regulatory commission, usually on the basis of details provided to the commission to prepare Power Purchase Agreements—nuclear tariffs are set by the Department of Atomic Energy with no external oversight. One simply doesn't know how these are computed. Therefore, it is not possible to compare those with, say, tariffs from coal-based thermal plants, which may be calculated using a different methodology.

Several government institutions and policymakers have criticized the DAE's tariff setting procedures. Ashok Parthasarathi, science adviser to Prime Minister Indira Gandhi, recalls a discussion with Homi Sethna, the then director of BARC, around the time the Tarapur Atomic Power Station was commissioned in 1969. Parthasarathi, who was then a member of the DAE, found that the tariff for power from TAPS did not include the fuel costs. When asked about this, Sethna's response 'implied that [adding this] would raise the cost of power from our reactors to "unacceptable" levels' (Parthasarathi 2007, 18–19).[20]

In 1985–86, the Comptroller and Auditor General examined the tariff for the MAPS reactor and found numerous problems (Bhargava 1992, 740). This included inadequate provisions for decommissioning, repairs and waste management. Even without taking these factors into account, CAG found that the rate of return on capital was only 3.5 per cent and not the 12 per cent expected of power projects.

The thirty-second report of the Lok Sabha Standing Committee on Energy in 2003 was explicit in trying to get nuclear power to compete fairly with other sources of power.

> The Committee find that fixation of tariff for Nuclear Power Plants is not within the purview of the Central Electricity Regulatory Commission (CERC). The Department of Atomic Energy (DAE) determine such tariff after due consultation with the Central

Electricity Authority (CEA). The Committee are of the opinion that while determining tariff, certain factors which encourage competition, efficiency, economic use of resources, good performance, optimum investment and similar other parameters should govern tariff fixation by CERC so that uniformity in tariff fixation between nuclear and non-nuclear power stations is achieved … the Committee … in their 31st Report … have recommended applicability of CERC over tariff for nuclear power so as to ensure a level playing field. The Committee would like to recommend that CERC should also fix tariff for nuclear power. (Standing Committee on Energy 2003a, para 2.95)

So far, this has not been implemented.

In order to compare expenditures or revenues that are spread out over time, economists and project analysts adopt what is called the discounted cash flow (DCF) methodology to carry out the economic analysis of any investment (Brealey and Myers 2000). The principle underlying this approach is that money received today is worth more than the same amount of money received later; for example, at an effective annual interest (or discount) rate of 10 per cent, today's one rupee would be equivalent to Rs 1.10 one year from now.[21] Therefore, the timing of cash inflows and outflows is important. In the DCF approach, all costs are discounted to some arbitrary but fixed reference date; the total cost reckoned at this reference point is the sum of the present values (PV) or future values (FV) of costs discounted to this date. Similarly one can calculate the present value of the revenues from the expected sale of electricity from the project. The levelized cost of electricity generation is then determined by setting the sum of discounted costs equal to the sum of discounted revenues. The DCF approach allows for evaluating the trade-off between front- and back-loaded cost streams, as well as taking into account construction periods.

All this is typically done before embarking upon a project so that planners can decide whether the investment is economically sensible. There is, then, the problem of estimating all this in advance.

> Accurate estimates of the cost of building the station depend in turn on accurate estimates of the cost of materials and labour; of the time taken to complete the station and bring it on stream; and of the long-term behaviour of the rates of interest to be paid on the capital involved. The estimated cost of building the station should also take into account the estimated cost of eventual decommissioning and dismantling. Accurate estimates of running costs depend in turn on accurate estimates of the cost of raw uranium; of enrichment if necessary; of fuel fabrication; of reprocessing or other means of management of spent fuel; of final disposal of high-level and other radioactive wastes; and of the specialized security measures required for the protection of fissile materials. The possible income from the station will depend on the eventual price and saleability of

> the electricity produced—a decade and more hence; and on the station's performance—in particular how its actual performance compares to the design specifications used as a basis for the original investment analysis. All of the above listed estimated quantities have proved difficult to get right, and spectacularly easy to get wrong. (Patterson 1976, 131)

This elaboration by Walter Patterson of the problems with estimating nuclear costs from more than thirty years ago still holds true. Table 2.1: Capital Costs of Operating Reactors in chapter 2 shows, for example, how the capital costs of all reactors constructed so far in India have significantly exceeded initial estimates. These cost increases were not confined to just one or two items of expenditure. For example, in the case of the Narora reactors, a 1988 study by the Comptroller and Auditor General of India listed ten major heads of expenditure that had cost overruns of 188 per cent or more (CAG 1988).

Though all the multiple variables identified above affect the cost of electricity generation, there are three critical parameters that overwhelmingly determine the economics of nuclear power (Ramana 2009a). They are the construction cost, the time taken to construct the reactor and the discount rate. Earlier, the performance of nuclear reactors, as measured by indices such as outage rates and capacity factors, had a large influence on the cost of nuclear power, but in recent decades reactor performances have improved markedly, at least in the United States, and this issue is now only of secondary significance in cost calculations (Kazimi and Todreas 1999). Performance indicators in the DAE's reactors, as documented in chapter 2, have been less remarkable.

Another significant variable is the period of construction, which determines the length of time for which capital is locked up without any revenues coming in from the sale of electricity.[22] This affects the economics and when electricity will be available—a consideration when generation shortfalls and an inability to meet the demand are a matter of immediate concern. All else being equal, typically, a plant that generates power earlier rather than later would be preferable.[23]

Among electricity generation technologies, with the exception of large hydroelectric projects, nuclear reactors have typically taken the longest to build. Table 6.1 shows construction times, measured from the first pour of concrete to the first grid connection of the unit, for reactors around the world that were commissioned during the specified periods.

TABLE 6.1: WORLDWIDE CONSTRUCTION TIMES FOR NUCLEAR REACTORS

Period	Number of Reactors	Average Construction Duration (Months)
1976–80	86	74
1981–85	131	99
1986–90	85	95
1991–95	29	104
1996–2000	23	146
2001–05	20	64
2006	2	77
2007	3	80

Source: IAEA 2008a, 23.

Note: The figures for the period after 2000 are mainly those of reactors constructed in East Asia and do not appear to include figures for some reactors that were under construction for over fifteen years.

In the light of this experience, NPCIL's assumption that new nuclear reactors will take only five years to construct (Thakur and Chaurasia 2005, 10) seems unjustified. The only two reactors in India that have taken such a short time to construct are TAPS I and II that were built on a special turnkey contract; the short period may well have had something to do with the numerous problems the reactors experienced in their operations (see chapter 2). Other reactors have taken from 100 months to 169 months (Bohra and Sharma 2006, 846).

Lest one assume that these delays are a feature of the past, the experience with the most recently constructed reactors provides evidence for the likely persistence of this trend. The first pour of concrete for the RAPS V reactor was in September 2002, and it was commissioned in February 2010, a total of eighty-nine months, roughly 50 per cent more than the NPCIL assumed. The wide variation in construction times is as important as the fact that they take long to construct since it adds to financial uncertainties about when the reactor will start generating revenues and the likely cost overruns as a result of delays.

The choice of discount rate greatly affects the levelized cost and, therefore, any comparisons of electricity generation costs. There is no consensus on what the discount rate should be since it is an expression of how planners wish to allocate resources and how they value future benefits in comparison with current sacrifices.[24] In those cases where private markets finance the nuclear reactor—which could be either debt or equity, that is, borrowing money or offering ownership of a part of the project—the discount rate would be the weighted average of the interest rate and the equity return rate. But these rates depend in part on the financial risk perception of nuclear technology on the part of investors.

The discount rates that are used for other electricity generation technologies may not be suitable for nuclear power for two reasons. The first is because nuclear power involves higher fixed costs as compared to, say, coal plants which have higher fuelling costs. Fixed costs are those that have to be borne regardless of whether the plant is operating or not. Fuelling costs, on the other hand, do not occur if the plant is not operating. In the event of a plant being shut down because of, say, lack of demand or an accident, the fixed costs—for example, loan repayments or salaries for some of the key employees—would have to be paid, whereas the fuel need not be purchased. It is for this reason that economists point out that plants with higher fixed costs, such as nuclear power stations, carry higher risks (Hamada 1972; Lev 1974; Mandlekar and Rhee 1984). Nuclear plants fall into this category.

In the United States, economist Stephen Farber compared the behaviour of stock prices of thirty-six utilities that had constructed nuclear reactors with twenty-five utilities that had never constructed nuclear reactors. He found that the market had deemed the utility's adoption of nuclear reactors as a risky proposition by demanding higher returns (Farber 1991). This was a routine effect, that is, it did not include the impact of accidents.[25]

The same idea has been expressed more recently in response to some US utilities seeking to build nuclear reactors to take advantage of the subsidies offered by the George W. Bush administration. The credit-rating agency Standard & Poor's has maintained that nuclear generation has 'the highest overall business risk compared with other types of generation' (S&P 2006). In May 2008, the other leading Wall Street credit-rating agency Moody's, which ranks the creditworthiness of borrowing companies, observed that a 'utility that builds a new nuclear power plant may experience an approximately 25%–30% deterioration in cash-flow-related credit metrics' (Moody's 2008, 2). Other financial market analysts suggest that 'U.S. utilities seeking to build new nuclear power plants could see their excellent credit ratings drop to a single "B" rating … [and] that utilities could do little to salvage their credit ratings' (Squassoni 2009, 31).

The second factor that makes nuclear power financially risky is the possibility of catastrophic accidents.[26] Both the Three Mile Island accident and Chernobyl resulted in negative, though transitory, price reactions amongst US electric utilities, with the effect becoming greater with increasing nuclear share of the utility's holdings (Hill and Schneeweis 1983; Kalra, Henderson Jr, and Raines 1993). Similar results are emerging in the wake of the Fukushima accidents.

Within the methodology of discounted cash flows, all these different financial risks translate primarily to a higher discount rate for nuclear power as compared to other forms of electricity generation. So, in some of the calculations shown below, a real discount rate of 6 per cent has been adopted.[27]

PRESSURIZED HEAVY WATER REACTORS

The 1999 claim about nuclear power being competitive with thermal power at a distance of 1200 km from coal mines was published in the Nuclear Power Corporation's in-house journal *Nu-Power*. This article summarized an NPCIL study on the 'longterm cost effectiveness of nuclear power'. Since the article did not provide most of the technical details, I wrote to NPCIL asking for a copy of the study. There was no response. After another email that got no response, I visited their office in Mumbai and asked for the report. The spokesperson told me that the study was an internal one and not available to the public. Therefore, it was not possible to look at the assumptions underlying the assertion.

One set of crucial assumptions was, however, listed in the summary article: the capital costs of the nuclear reactor and the coal plant were taken as Rs 5.23 crore and Rs 3.75 crore per megawatt of generating capacity, respectively.[28] Knowing the history of cost overruns at the DAE reactors, I was suspicious of the former assumption and wondered if this choice of a rather arbitrary—anticipated or projected—figure was most likely to be the determinant of the result on economic competitiveness.

Given that a number of reactors have been constructed, it was more rigorous to base one's economic comparison on empirical grounds and start with the costs of some actual reactors. Therefore, in collaboration with Amulya Reddy and Antonette D'Sa, who had performed the earlier comparative costing of different technologies, I started looking at the costs of generating electricity from the first two units of the Kaiga Atomic Power Station (Kaiga I and II) that were commissioned in 1999.[29] At the time that we started performing the economic analyses, they, along with the RAPS III and IV reactors, were the newest reactors. It was expected, therefore, that these would have incorporated the lessons of the DAE's experiences with earlier reactors, and would also be indicative of the future as far as similar reactors are concerned.

However, to bend over backwards to favour the nuclear case, we also included the yet-to-be-commissioned Kaiga III and IV reactors even though the values for some (but not all) of the data for these plants had no empirical basis and involves guesses and estimates. In doing so, we were assuming that the values for construction time, performance, and input costs would be as per expectations. This has turned out not to be the case. At that time, NPCIL expected that they would be commissioned in December 2006 and 2007. While Kaiga III was commissioned in May 2007, about six months behind schedule, Kaiga IV was commissioned in January 2011, more than four years late. A second reason for choosing these plants was that they might be expected to have lower capital costs since the expenses involved in site development would have been covered by Kaiga I and II.

For calculating the cost of producing electricity from coal, we chose the case of the Raichur VII Power Station (RTPS VII). Like the Kaiga I and II reactors, RTPS VII too was a relatively recent plant. Its capacity of 210 MW is roughly the same as each of the Kaiga reactors, and is an example of multiple projects at the same location (just as Kaiga III and IV are co-located with Kaiga I and II). Being in the same geographical region, it feeds into the same grid and therefore faces roughly similar problems from grid instabilities.

In addition to the construction costs, we included a number of other expenses.[30] For both cases, this included fuelling as well as operations and maintenance expenses. For coal plants, we included the cost of furnace oil. Specific to nuclear power were the costs of the initial loading of heavy water and uranium and that of replacing the heavy water that is lost during routine operations. The data for these were not easy to obtain and we drew upon a range of publications—annual reports, publications and presentation in technical conferences by authors from the Department of Atomic Energy, Government of India audits, newspaper articles and international figures.

In both cases, we included waste-management expenses, but in different ways. For nuclear power, we followed the DAE in imposing only a nominal charge for dealing with radioactive waste (that came out to about two paise per kWh) and excluding the cost of reprocessing spent fuel.[31] For thermal power, we assumed that, contrary to actual practice, RTPS VII would have to spend Rs 174 to dispose of each tonne of fly ash that is generated while burning coal.[32] In fact, the fly ash is used to make saleable products like mosaic tiles and bricks and, hence, the power plant does not pay anything for its disposal (Ghanashyam 2006; *Hindu* 2006b).

The last is but one of a number of assumptions favourable to nuclear power economics. Another example is the assumption that the RTPS VII station has an economical lifetime of thirty years as opposed to forty years for the Kaiga reactors. Finally, and perhaps most significantly, we assumed that the coal used in it came from mines that were 1400 km away, thereby increasing its fuel costs, which dominate the cost of producing electricity at thermal plants. This was somewhat atypical. Around the time we were doing our analysis, over a third of all of India's coal plants were at the pithead and another one quarter or more were within 500 km of one (Chowdhary 1998).

Besides the cost of constructing the reactor, an important component of the total cost of getting a heavy water reactor to start operating is the cost of loading it with heavy water. Each 220-MW reactor, like the ones at Kaiga, requires 70 and 140 tonnes of this substance for the initial coolant and the moderator inventory, respectively (NEI 1994, 72).

The Nuclear Power Corporation reportedly treats the initial HW requirements as a non-depreciating asset that is leased from the DAE (Muralidharan 1988, 191). In the discounted cash-flow methodology, however, the correct way to include this component is to treat the initial inventory as an upfront capital cost. And then, at the end of the economic lifetime of the reactor when the ('leased') HW is returned to the DAE, there is a cash inflow, which must be discounted to the time of commissioning. This methodological detail apart, the most pertinent fact about heavy water is that it is very expensive to produce. As discussed in chapter 5, each kilogram of the substance requires upwards of Rs 20,000 to manufacture.

There are, of course, several such intricacies but the reason for highlighting heavy water is that it subsequently became a major point of debate. After our results were examined by reviewers, and the *Economic and Political Weekly* published our paper, Sudhinder Thakur, executive director of NPCIL, responded to our paper in print (S. Thakur 2005). Though Thakur's basic purpose was to reiterate the claim that nuclear power was competitive, we were pleasantly surprised and welcomed his attempt to correct some of our assumptions. That was, after all, how policy issues should be debated and decided upon.

Thakur pointed out three factors on which we had erred in our paper. One was the amount of electricity consumed by the reactors on site, what is called auxiliary consumption. Since there was no data specific to the Kaiga reactors, we had estimated this to be 12 per cent of the generation by looking at actual figures for gross generation and net exports at all of the DAE's nuclear reactors as published in the DAE's performance budgets.[33] We had averaged these and assumed 12 per cent for the in-plant consumption in the case of the Kaiga reactors. Thakur cited 'NPCIL internal reports on generation' to claim that the auxiliary consumption at the Kaiga reactors was only 9.5 per cent. Because this is lower than average, some other reactors must have higher auxiliary consumptions so that the mean comes out to be 12 per cent.

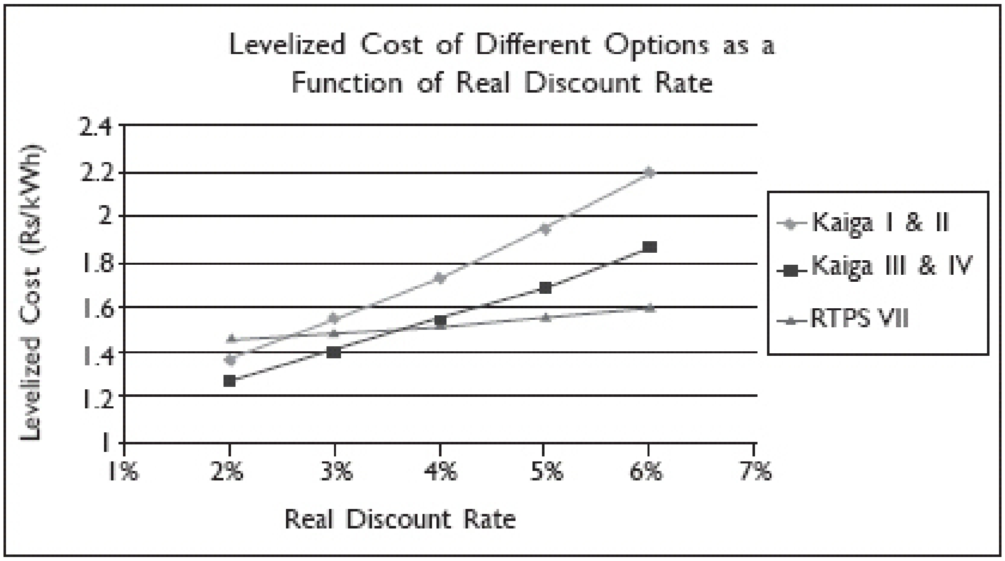
The second factor was the capital cost estimate for the Kaiga III and IV reactors. Because NPCIL had not responded to our questions about the annual break-up and other financial details, we had used some figures from the DAE performance budget of 2002 to estimate the necessary pieces of information. Thakur offered alternate figures in his article.

Finally, the most significant difference between our estimates and NPCIL's assessment of nuclear economics was due to the cost of heavy water. In our paper, we had pointed out that the cost of heavy water produced in the DAE plants has been a matter of dispute.[34] Since the newer plants appeared to be performing better, we had used the cost of production at the most recently commissioned heavy water plant at Manuguru as estimated by the Comptroller and Auditor General. This turned out to be Rs 24,880/kg at 2002 prices.[35] Thakur, on the other hand, informed us that the actual rate for the year 2003 as notified by the government, that is, DAE, was Rs 12,525/kg. This was roughly half our value and an important source of difference in our estimates.

Subsequently, I published two papers, one a direct response to Thakur's paper,[36] and the second, examining the production of heavy water and showing that the DAE's price was a significant subsidy.[37] But the essence of the first paper was to accept Thakur's suggestions on the first two factors: auxiliary consumption and capital costs for Kaiga reactors. I then compared the cost of nuclear power with coal power for both the cases of heavy water at Rs 24,880/kg and Rs 12,525/kg. It turned out that even in the latter case nuclear power could not be considered really competitive.[38] The results shown below reflect the revised values for the first two factors.

We chose to present our results as a function of the discount rate. Because nuclear power and thermal power are different in what contributes to their costs—the capital costs for nuclear power and coal for thermal power—their relative economics would depend on the discount rate. What we found was that while nuclear power was cheaper for low discount rates, as these discount rates became bigger, coal power became cheaper above some crossover point (see Figure 6.1).

FIGURE 6.1: BUSBAR GENERATION COSTS OF KAIGA I AND II, KAIGA III AND IV (PROJECTED COSTS), AND RTPS VII AT 80 PER CENT CAPACITY FACTOR



The crossover point depended on whether we were comparing the reactors already constructed, or the reactors for which we had only projected data. When it was for the Kaiga I and II reactors that had already been constructed, the crossover value was about 2.7 per cent if a heavy water cost of Rs 24,880/kg were used. For the Kaiga III and IV reactors, this crossover value was about 3.9 per cent. While there is a debate on the appropriate discount rate for public investments, few would argue that these are high rates for long-term investments, especially in a country with multiple demands for capital. Thus, if the subsidy on heavy water were removed, nuclear power from the Kaiga reactors would be more expensive than thermal power from a coal plant that is assumed to be 1400 km away from mines.

What if the 'government-notified price' of Rs 12,525/kg were used? Again, the answer would depend on which reactors were considered: the already constructed reactors for which construction costs are known or the reactors for which only projected values are available? For the former case, that is, the Kaiga I and II reactors, the crossover point is the low figure of 3.8 per cent. For the latter, it is less than 5.7 per cent. This value is relatively close to, though less than, what is used by government planners (D.K. Bose 2000; Public Accounts Committee [1991–92] 1992, 3). However, most studies that compare electricity generation (or saving) technologies use values that range from 8 per cent to 10 per cent (see, for example, Shukla, Ghosh, and Garg 2003, 15; Nouni, Mullick, and Kandpal 2006, 3732). If one were to look to stock market returns as a measure of the cost of capital, return rates have been over 17 per cent on average between 1981 and 2005 (Varma and Barua 2006). Thus, if the Nuclear Power Corporation had to raise money on the capital markets, it would certainly be unable to claim that the power it generates is competitive.

We also looked at the sensitivity of our results to various factors. For example, we varied the efficiency with which the power plant (expressed through the capacity factor) operates and found that lower capacity factors reduce the competitiveness of nuclear power. Similarly, if the economic lifetime of the coal plant were assumed to be the same as that of the nuclear plant, that is, forty years, the crossover points would reduce substantially, and nuclear power would be more expensive for a larger range of discount rates. Finally, if, as argued by economists, the greater financial risk in the case of nuclear power is translated into different discount rates for the two forms of generation, then nuclear power would be even less competitive.

Though our results are for the specific cases of Kaiga and RTPS VII which, as I have argued, do offer a fair point of comparison, the basic point should hold true for other cases, and one could conclude that nuclear power from heavy water reactors would generally be costlier than thermal power.

THE FAST BREEDER REACTOR

The natural question that may come up at this point is what the economics of nuclear power would look like in the future. In the early years of this century, a group in the DAE developed a scenario for the growth of electrical energy in India, envisioning the total electricity generation by the middle of the century growing by an order of magnitude (Grover and Chandra 2004). The question then was, which sources of generation would have to be tapped and, quite naturally, the DAE answered it by postulating a scenario in which ‘the nuclear contribution towards electricity generation will increase from the present 3 per cent to about a quarter of the total’ (Srinivasan, Grover, and Bhardwaj 2005, 5183). In order to achieve this, the installed nuclear capacity was to grow to 275,000 MW by 2052. The suggested route to this expansion was through fast breeder reactors, which were to constitute 262,500 MW of this total capacity (Grover and Chandra 2006, 2844).[39] Recently, these figures have gone up even further, again with the bulk of the generation capacity coming from breeder reactors.

The DAE’s interest in breeders—as discussed elsewhere in this book—goes back to the 1950s. And during that period, the DAE’s keenness on developing breeder reactors was not exceptional. Several countries around the world spent large quantities of money on research and development related to breeders; about half a dozen countries constructed pilot-scale or demonstration breeder reactors (IPFM 2010a). However, over the decades, most have suspended their programmes. For example, even France, the country that has actually gone on from the demonstration-level to building and operating the commercial-scale Superphénix reactor, has not planned for the construction of any future breeders.

Economics was an important cause for disenchantment with breeders. Several studies have shown that electricity from breeder reactors is expensive in comparison to that from light water reactors that dominate the world’s nuclear capacity (Cochran 1974; Feiveson, von Hippel, and Williams 1979; Chow 1995; Bunn et al. 2005).[40] In contrast, the DAE has long claimed that electricity from breeder reactors is comparable to the corresponding cost of electricity from a PHWR, the reactor type that accounts for the largest share of nuclear generation in the country (Paranjpe 1991, 1.4–4; Bhoje 2003, 10).[41]

Again, the DAE offered no real economic analysis to back up this claim. My colleague Suchitra and I started examining this issue soon after the construction of the first commercial-scale breeder reactor, the PFBR, had started in 2004. This allowed us to base our calculations on a specific cost estimate rather than an abstract figure.

Just calculating the cost of generation does not make as much sense as comparing it with the cost of generation at another similar plant. The comparison we carried out was with the mainstay technology adopted by the

DAE itself—the PHWR. Around that time, the DAE announced that ‘future PHWRs … are planned to be only of 700-MW unit size’ (DAE 2005a, 26). The Nuclear Power Corporation’s assessments of nuclear power economics also started using these as the standard nuclear technology (Thakur and Chaurasia 2005). Therefore, it seemed that the right comparison would be between the PFBR and a 700-MW PHWR.

As with the comparison between the Kaiga and RTPS plants, we used cost figures from Government of India budget documents and DAE performance budgets as far as possible. Unfortunately, many cost elements were not available, especially the PFBR’s annual construction cost estimates and the fuel-chain costs. As described in the introduction, we tried using the Right to Information Act to acquire some of the information. Though BHAVINI did give us the PFBR’s annual construction cost estimates, it denied all information related to the fuel-chain costs, including the cost of fuel fabrication and reprocessing (Ananth 2006a; Suchitra and Ramana 2007). Therefore, we were forced to extrapolate from international cost figures or make our own calculations based on other Indian data.

We considered the same set of cost components for both the PFBR and the PHWR, namely, construction of the reactor (capital cost), fuelling, operations and maintenance, decommissioning, refurbishment, working capital and management of low-level radioactive wastes.[42] For the PHWR, the fuelling cost included the cost of uranium and the cost of fuel fabrication. Also included were the costs of the initial heavy water inventory and of replacing the heavy water that is lost during routine operations. For the PFBR, the fuelling cost included that of producing plutonium through reprocessing and fabricating it into MOX fuel.

The DAE has estimated the total construction cost of the PFBR to be Rs 34.92 billion, which translates into Rs 28.41 billion in 2004 rupees, (Ananth 2006a).[43] In terms of dollars per unit capacity, this converts to $1292/kW (in 2004 dollars). As a unit cost, this is much lower than estimates of breeder reactor construction costs elsewhere. For example, the Nuclear Energy Agency gives a range of $2000–2800/kW (in 2004 dollars) for MOX-fuelled fast reactors (NEA 2002a, 216). However, even this figure is much lower than what it has actually cost to construct breeder reactors.[44]

The projected cost of the PFBR falls well below both the NEA’s estimates and actual costs. There are also historical and technical reasons to expect that the PFBR’s cost will turn out to be higher than the DAE’s estimate.

Technically, breeder reactors can be expected to be more expensive for two reasons. First, the use of molten sodium as coolant brings with it several operational requirements, such as heating systems to keep the sodium molten at all times, and safety-related requirements, such as extensive firefighting equipment (Farmer 1984). The second reason stems from the realization that some accidents at breeder reactors could lead to the release of large quantities of explosive energies (Bethe and Tait 1956). Therefore, breeders have to include extensive safety features which are a significant component of the total capital cost.

Historically, as we have seen, every reactor constructed by the DAE has experienced cost overruns. Indeed, in August 2009, it was reported that the PFBR may end up costing Rs 50 billion, over 40 per cent more expensive than projected (Jagannathan 2009a). By November 2011, when approximately 80 per cent of the work on the reactor had been completed, the cost estimate had gone up to Rs 56.8 billion (Srikanth 2011). Despite these many reasons to expect cost escalation, we used the DAE's estimate so as to be favourable towards breeder economics.[45]

In economic terms, the primary material requirement for the PFBR is plutonium. As mentioned earlier, the DAE maintains that the plutonium is available 'free of cost' (Govindarajan 2003, IT-23/3). The essential argument for this assumption is that a breeder reactor produces more plutonium than it consumes. But this argument is financially unsound because the plutonium that is recovered by reprocessing the core will be available only years after the reactor starts generating electricity, with the period determined by the effective breeding ratio. Methodologically, the sound way of taking this future plutonium production into account is by adding the cost of plutonium for fuelling the reactor initially and providing a credit for the plutonium produced *when* it is recovered; the latter would have to be discounted to the same time as the initial plutonium procurement. The corresponding assumption for the PHWR is that the heavy water for the initial loading of the PHWR is purchased from the DAE (with a cash outflow) and resold when the reactor is shut down.

The PFBR design requires an initial inventory of over 1.9 tonnes of plutonium in its core (IAEA 2006, 32). Even though the rationale for breeder reactors is that they produce more plutonium than they consume, it should be obvious that the plutonium for the initial core has to come from elsewhere. In the DAE's scheme, this plutonium will be produced by reprocessing PHWR spent fuel at the Kalpakkam Atomic Reprocessing Plant, thus providing the link between the first and the second phases of the nuclear programme (Hibbs 2003, 9). The first few reloads would also have to come from the same source. [46]

Future reactors may also have to adopt the same practice of using plutonium from reprocessing PHWR spent fuel for the initial cores and the first few reloads. This is because the PFBR design has a relatively low breeding ratio of 1.04 (IGCAR 2004, 1.18), and, therefore, will not produce adequate amounts of plutonium to fuel other breeder reactors. [47]

As described in [48] Therefore, much of the plutonium that is used in the PFBR's initial loading would have been separated several years before it is fabricated into MOX fuel. As the plutonium ages, one of its isotopes, plutonium-241, decays into americium-241, another radioactive material that absorbs neutrons and lowers the amount of energy produced by the reactor. This would have to be chemically separated before the plutonium can be fabricated into MOX. [49] The cost of removing americium would have to be incurred only in the case of plutonium coming from KARP. [50]

Subsequently, the plutonium for the PFBR could be obtained from reprocessing its own spent fuel. Because of the higher plutonium content of the PFBR spent fuel, the cost of such plutonium would be lower. Again, our RTI request to BHAVINI for its estimate of the costs of removing americium and reprocessing PFBR spent fuel was denied. Based on construction costs of the reprocessing plant that deals with the spent fuel from the smaller FBTR and scaling it up, we estimated that the cost to produce each gram of plutonium through this route was about Rs 1900, much lower than the corresponding cost to obtain plutonium from KARP (Suchitra and Ramana 2011, 21–22). [51]

If the facility to reprocess the spent fuel from the PFBR is not ready by the time the first batch of spent fuel is unloaded and cooled, then the plutonium for further loadings would also have to be obtained from KARP. This seems entirely plausible since construction of the plant does not seem to have started. [52] Given the complicated nature of reprocessing plants, the DAE's very limited experience with reprocessing fast breeder spent fuel [53] and the experience of persistent delays in constructing reprocessing plants in India and elsewhere, [54] it is quite likely that the new reprocessing plant will not commence in time to deal with the first or even the second batch of spent fuel. If that were to be the case, then, the cost of plutonium used for reloading fuel in the PFBR would be higher.

This plutonium is converted to MOX fuel by mixing with uranium.[55] MOX fuel is much more expensive to fabricate than uranium fuel. This higher cost is related to two characteristics: the higher radioactivity of plutonium[56] and the higher density of heat production in the fuel used in breeder reactors.[57] Again, this was one of the cost details we requested in our RTI petition to BHAVINI, but were refused. Therefore, we adopted estimates provided by the Nuclear Energy Agency (NEA 2002a).[58]

In the case of the PHWR, we followed the DAE in most of its cost assumptions except for heavy water. For reasons explained earlier, we reckoned this at a higher cost. The Nuclear Power Corporation estimates that 700-MW PHWRs cost Rs 52 million/MW in 2005 prices (Thakur and Chaurasia 2005, 12). Thus, a 1400-MW PHWR power station will cost approximately Rs 70 billion in 2004 rupees.

Based on the methodology described above and the cost figures listed, we calculated that producing 1 kWh of electricity at the PFBR is 80 per cent more expensive than the corresponding cost from PHWR. We also carried out a number of sensitivity studies and showed that our basic conclusion about the much higher costs of generation at the PFBR holds true in all those situations (Suchitra and Ramana 2011). Therefore, it is a robust assessment. Thus, as with the comparison between Kaiga and RTPS, the DAE's assessment that breeder electricity is competitive is simply not borne out upon empirical examination. The main culprit this time is not heavy water, but plutonium, specifically the much higher costs associated with the production and fabrication of plutonium.[59]

The main argument offered by the DAE for the pursuit of breeders is that India has only 'modest uranium reserves' of about 60,000 tonnes, 'which can support 10,000 MWe (megawatt electric) of PHWR capacities' (Kakodkar 2006). This formulation, while widely articulated, is misleading. India's uranium resource base cannot be represented by a single number. As with any other mineral, at higher prices it becomes economic to mine ores of poor quality which are less accessible.

We therefore addressed the DAE's argument about limited uranium resources by considering a range of uranium costs in our comparison of electricity generation costs at breeder reactors and heavy water reactors (see

Figure 6.2). The difference in the generation costs decreases because of the increased cost of fuelling the PHWR. However, it is only when the uranium cost goes up to $1375/kg that the two generation costs become equal. This crossover cost is nearly seven times the base case of $200/kg.

FIGURE 6.2: SENSITIVITY TO URANIUM COST

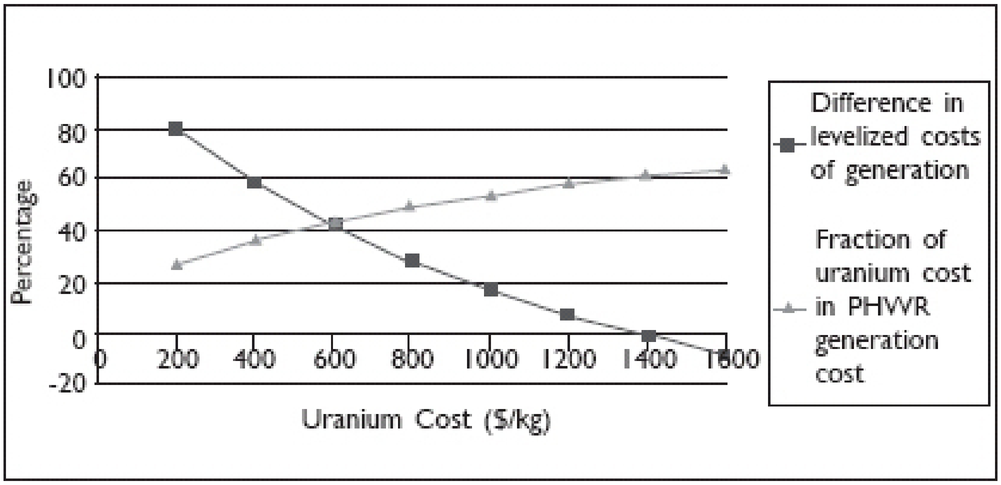


Figure 6.2 also shows the fraction that the cost of uranium (including that of fuel fabrication) contributes to the PHWR generation cost. While the plutonium-related costs constitute about 67 per cent of the PFBR generation cost in the base case, uranium-related costs exceed 50 per cent of the PHWR generation cost only at around $800/kg. In other words, the cost of generating electricity at PHWRs is only weakly dependent on the uranium cost. A reactor operator willing to incur such high costs for uranium would have access to much larger quantities of uranium than currently considered economically recoverable.

There is a general perception that uranium is a scarce resource. However uranium, as an element, is not all that rare, with an average concentration in the earth's crust of 2.8 parts per million (ppm), and is more abundant than silver or tungsten (Schneider and Sailor 2008, 380). Uranium deposits are found in several different kinds of rocks, such as sedimentary, igneous and metamorphic, as well as in seawater.[60]

Geologists have examined uranium ores present near the surface of the earth and have very roughly estimated the amount of uranium present as a function of grade. They find that the distribution of uranium in the earth's crust corresponds to a roughly three-hundred-fold increase in the estimated amount of recoverable uranium for every ten-fold decrease in the ore grade (Deffeyes and MacGregor 1980).[61]

There are different relationships possible between the ore grade and the cost of obtaining uranium from that ore (Schneider and Sailor 2008). The simplest assumption is that the cost of uranium mining is inversely proportional to the ore grade, and the price of uranium is directly proportional to the cost of mining.[62] Other models are somewhat more conservative. Using different models, we estimated that when the uranium cost goes up to $1375/kg, the availability of uranium increases by a factor of at least about 60 and possibly about 120. In any case, lack of uranium reserves is unlikely to be a limiting factor for the expansion of nuclear power based on PHWRs for decades.[63]

The preceding discussion is not meant to imply that, instead of a breeder programme, a large-scale expansion of nuclear power based on heavy water reactors using high-cost uranium is being recommended. That would imply widespread uranium mining using ores of poor quality with significant environmental and public health impacts. The point of our discussion of uranium availability is to demonstrate that the DAE has not undertaken the most elementary economic analysis necessary to justify the breeder programme.

In his *Hind Swaraj*, Mahatma Gandhi made a remarkably prescient observation: 'The systems which the Europeans have discarded are the systems in vogue among us. Their learned men continually make changes. We ignorantly adhere to their cast-off systems' (Gandhi 1997, 103). The DAE's pursuit of breeder reactors when countries in the West have abandoned them for all practical purposes offers an excellent but unfortunate example of such ignorant adherence.

IMPORTED LIGHT WATER REACTORS

What about the reactors that the NPCIL is planning to import as a result of the special waiver by the Nuclear Suppliers Group in September 2008? Ever since 2005, when the US–India nuclear deal was first made public, there has been a string of official and unofficial pronouncements on how many reactors were going to be imported.[64] As the previous discussion would lead one to expect, the major problem which imported nuclear reactors will face is the high cost of electricity generation as a result of high capital costs, a factor that has increased in salience as estimated costs of new nuclear reactors mount.

The expectation of high capital costs has been borne out by recent estimates from the United States and Western Europe. According to a report released by the French government's Court of Audit in January 2012, the current cost estimates of the only reactor under construction in France at Flamanville is 6 billion euros, which translates to about $4500/kW (Chaffee 2012, 3). The US Energy Information Administration estimates that a new nuclear plant could have an overnight cost of $5335/kW (EIA 2010, 7). In comparison, the DAE's estimates of recently completed PHWRs are all around $1500/kW (Bohra and Sharma 2006).

This problem was recognized well before negotiations on the deal began. In 2003, former AEC chairman M.R. Srinivasan stated that 'Recent cost projections show that if an LWR were to be imported from France, the cost of electricity would be too high for the Indian consumer. This is because of the high capital cost of French supplied equipment' (M.R. Srinivasan 2003). Indian nuclear officials have set their hopes on licensed domestic manufacturing. In the words of Sudhinder Thakur, executive director of the state-owned Nuclear Power Corporation, 'When you build a reactor here, costs come down dramatically' (Jishnu 2008).

Just how much of a dramatic cost reduction is necessary for nuclear power to become competitive with its favourite competitor, coal, becomes clear in a paper by Thakur (2008). The aim of the analysis was laid out explicitly:

> The initiatives of the Indian government on international cooperation in nuclear energy and the option of a significant increase of the nuclear share in electricity generation based on nuclear power reactors set up with international cooperation … have stirred up a debate in the country on these issues … there is apprehension in some sections that the likely tariffs of electricity generated by large imported nuclear power reactors would be unaffordable. This paper … demonstrates that these tariffs would be competitive with other options for large base load generation across a range of overnight costs and fuel prices.

The analysis, however, shows nothing of the sort. Thakur starts off by considering a 'base case of overnight costs of $1500/kWe at 2007 prices' (S. Thakur 2008). Compared to estimates in excess of $4500/kW, this is absurdly low. Why has this been assumed? The answer has to do with the cost of coal power. It turns out from Thakur's analysis that when the cost of an imported LWR goes above $1600/kW, electricity from coal will become cheaper.

What are the chances for such a drastic cost reduction in reactor costs? One handle on this question might be to look at another country that also claims to have reduced costs because of cheaper labour: China. The estimated overnight construction cost of imported AP1000 LWRs in China is $2302/kW (NEA

2010a). Similarly, the cost of the two EPR-1600s from Areva to be constructed at Taishan has been reported to be $7.3 billion (WNA 2010). There have been some reports of price increases (Chaffee 2011), and one has to wait for the completion of construction before one knows what the final figures are. Even current estimates, though, imply a much higher overnight construction cost than the $1500/kW assumed by S. Thakur (2008).[65]

All these costs are so significant that importing 10,000 MW or so of foreign reactors would cost trillions of rupees.[66] These costs would ultimately have to be paid by electricity consumers through their monthly bills. If the government decides to subsidize some of these costs, then a part of this may be borne by the citizens regardless of whether or not they get any electricity.[67] But, basing plans on subsidies is not a recipe for a large-scale expansion of nuclear power in the country.

The poor economics of nuclear power may not be a major source of concern to private business houses such as Tata and Reliance which want to enter the nuclear reactor operations business. The expectation among private companies is that they would be able to secure agreements with the electricity regulatory commissions guaranteeing them a price that would allow for recovery of costs and a reasonable rate of return on costs. At least with the governments of the last two decades, they are also confident of having their profit interests protected.[68] However, as in the case of NPCIL, this protection would be at a cost to the citizen.

GAMES PEOPLE PLAY

If nuclear power is uncompetitive, then why do many people believe that it is cheap? In part, this is because, at every opportunity, the nuclear establishment keeps repeating the claim about the competitiveness of nuclear power. It also tries to substantiate it through ‘calculations’. These calculations, however, are flawed. Typically, they are based on estimated costs of future facilities rather than actual costs of facilities already constructed. Given the huge cost overruns at most facilities, as documented in chapter 2, the distortion due to this practice is significant. Then, it makes assumptions about other cost components, with no support from data of any sort. For instance, the operations and maintenance cost is merely pegged at a specific percentage of the capital cost, with no basis for arriving at it. The costs of decommissioning a reactor are accounted for by periodically adding a set amount of money, called a decommissioning levy, into a fund (Sebastian, Mago, and Ramam 2001). But there is no reliable estimate of how much decommissioning a reactor will cost, and the few examples in other countries that have decommissioned reactors have invariably shown costs much more than expected. Similarly, the cost of radioactive waste management is completely arbitrary (typically, Rs 0.05 per unit).

One reason that the nuclear establishment gives for not relying on past experience with costs is the possibility of technological and organizational learning leading to lower costs in the future. However, historically, learning in the nuclear field has been limited at best. In the United States—the country with the most nuclear reactors—construction costs grew steadily from $1279/kW (in 2006 dollars) for reactors commissioned between 1966–67 to $4377/kW (in 2006 dollars) for reactors commissioned a decade later (CBO 2008). The steady growth in costs persisted even in later reactors (Hultman and Koomey 2007). Similarly, during the late 1970s and 1980s, the period when France brought online most of its current nuclear power plants, the capital costs (measured in constant francs) increased with time (Grubler 2009). This tendency continues: the current cost estimate of the Flamanville plant being constructed in France is about 2.4 times the average per-unit cost of the existing fleet (Chaffee 2012, 3).

In addition, there are various subsidies. As discussed earlier, the DAE takes care of the costs of dealing with spent fuel, which contains the bulk of the radioactivity produced during reactor operations, thereby subsidizing waste management. It provides the plutonium obtained to the breeder programme at no cost. The DAE also provides heavy water at a subsidized cost. Nuclear power has been favoured with fiscal concessions, such as customs duty waivers on import of equipment and tax holidays (FE 2000; DAE 2002a).

A somewhat more subtle subsidy extended to the nuclear establishment is due to the risk of catastrophic accidents. The impact of such an accident would be disastrous, especially in a country like India with a large agricultural sector. Prior to the US–India deal, the implicit assumption was that the government would take care of the immense costs of dealing with a potential accident. That represents a subsidy to the nuclear establishment.

Following the deal, there are plans to import nuclear reactors from international vendors. Independently, there are domestic big businesses which would like to come into the nuclear business because the potential profits are so huge. Neither of them wants to be held liable for compensating the full range of damages in the event of an accident since they might be bankrupted. To appease these constituencies, the Manmohan Singh government got a nuclear liability bill passed in Parliament, which limited the liability of the operator of a nuclear power plant to a mere Rs 15 billion, and the Government of India's own liability cap to roughly $450 million. In comparison, official government estimates of the cost of the 1986 Chernobyl accident run into hundreds of billions of US dollars. The difference between the operator's liability cap and the government's liability cap amounts to a subsidy to nuclear power. The rest of the risk associated with a really catastrophic accident whose damage exceeds the government's cap would be borne by the victims or society at large. Therefore, the profits are privatized, but part of the risk is socialized. It would also implicitly be providing perverse incentives for operators and suppliers of nuclear plants to cut costs at the expense of safety (Raju and Ramana 2010b). This creates a classic example of what in insurance parlance is called a 'moral hazard': insulating a party from risk has a distorting effect on its behaviour (Raju and Ramana 2010a).

All in all, there is much evidence that the DAE is not really serious about economic considerations. The latter proposition is illustrated by Bhabha's oft-quoted dictum: 'There is no form of power as expensive as no power, that is, doing without power altogether' (Jain 1974, 153).[69] While it is true that doing without power does pose costs on individuals and society, the question is not of whether or not power should be generated in the first place.[70] The question is which combination of generating technologies should be used. This question is most often decided—at least theoretically—through comparative costing and least-cost methods of analyses.[71] But, for the multiple reasons mentioned above, official efforts at comparative costing, especially those of the DAE, make a capital-intensive source of power like nuclear energy seem more economical than it really is. The result has been to bear out I.M.D Little's prognosis from 1958: 'As Dr Bhabha says, electricity is in short supply in India. It is likely to go on being in short supply if one uses twice as much capital as is needed to get more' (Little 1958, 1486).

7

Safety

> *When anyone asks me how I can best describe my experiences of nearly forty years at sea, I merely say, uneventful. Of course, there have been winter gales and storms and fog and the like, but in all my experience, I have never been in any accident of any sort worth speaking about. ... I never saw a wreck and have never been wrecked, nor was I ever in any predicament that threatened to end in disaster of any sort.*
>
> *I will say that I cannot imagine any condition which would cause a ship to founder. I cannot conceive of any vital disaster happening to this vessel. Modern shipbuilding has gone beyond that.*
>
> —Captain Smith, Commander of the *Titanic*[1]

In its submission to the International Atomic Energy Agency (IAEA) as part of its responsibilities under the 1994 Convention on Nuclear Safety, the DAE stated:

> Safety is accorded overriding priority in all activities.[2] All nuclear facilities are sited, designed, constructed, commissioned and operated in accordance with strict quality and safety standards … As a result, India's safety record has been excellent in over 260 reactor years of operation of power reactors and various other applications. (GoI 2007, 3)

Is this assertion true? This chapter tries to evaluate the DAE's claims by examining the historical record of safety performance at the DAE's facilities. This record shows that nearly all the nuclear reactors and other facilities associated with the nuclear fuel cycle operated by the DAE have had accidents of varying severity. These have been euphemistically termed 'incidents', primarily to mollify public concern. Between 1998 and 2010, there have been between twenty-one and fifty-four incidents (average thirty-four) every year, according to the Atomic Energy Regulatory Board annual reports (AERB 2001, 2002, 2003, 2004a, 2007, 2008, 2009, 2010, 2011).[3] Although none of these may have resulted in large-scale damage, ignoring them is not justified.[4] An analogy might help. Various symptoms that a patient might experience, such as shortness of breath or frequent chest pain, are typically indicators of a deeper problem, such as clogged arteries, and potential precursors of major heart attacks. In the same way, these small mishaps are also often indicators of potential accidents. Further, the pattern of failures at the DAE's facilities is suggestive of deeper problems, in particular, inadequate institutional priority to safety.

Another lens to examine the priority accorded to safety is the kind of choices made during the design of reactors. In the case of the PFBR, numerous design choices—most probably motivated by cost-cutting—have made the reactor more vulnerable to severe accidents and the impacts of such an accident more catastrophic. A different manifestation of the low priority to safety has been the regulatory structure which is, in effect, not independent of the nuclear establishment. All this is exacerbated by unjustified confidence in the safety of its facilities.

This state of affair is dangerous. Among all electricity-generating technologies, nuclear energy alone is prone to catastrophic accidents with potentially global impact, leaving fallout that may stay hazardous for decades, if not centuries. Poor safety culture increases the likelihood of such accidents. The likelihood of accidents will also increase as the number of nuclear reactors and other facilities go up. Unless there is a significant change in the organization managing the technology, the prospect of hundreds of nuclear reactors around the country does bring with it grave risks, and should be a cause of concern for all.

ORGANIZATION

One reflection of the attitude of the DAE towards safety is its institutional structure. Till 1972, it did not have a separate, identifiable organization or personnel to review safety of its nuclear installations (Gopalakrishnan 2002, 384).[5] In February 1972, the DAE constituted an internal Safety Review Committee (SRC) to oversee safety at DAE facilities (R. Shankar 2008, 18). But this was a purely internal organization and there must have been severe conflicts of priorities.

As early as the 1970s, even before any special safety agency was created, Ashok Parthasarathi, a senior bureaucrat, had suggested that the 'inspection of all nuclear installations from the point of view of health and environmental safety should be administered by a body with a suitable name and located in Department of Science and Technology, as that department had been assigned the national responsibility for ensuring the preservation of environmental quality' (Parthasarathi 2007, 131–32). But this was not accepted by the Atomic Energy Commission.

In 1979, after the Three Mile Island accident in the United States, the DAE constituted a committee to review 'the specific functions and responsibilities of DAE–SRC in order to enable DAE to discharge its obligations under the Atomic Energy Act' (Sundararajan, Parthasarathy, and Sinha 2008, iii). The committee recommended 'the creation of Atomic Energy Regulatory Board by the Atomic Energy Commission with powers to lay down safety standards and assist DAE in framing rules and regulations for enforcing regulatory and safety requirements'. In 1983, the Atomic Energy Regulatory Board (AERB) was set up to oversee and enforce safety in *all* nuclear operations. But in 2000, facilities that were involved, even if peripherally, in the nuclear weapons programme, were excluded from the AERB's purview.

The AERB's effectiveness is constrained by the AEC's choice of institutional structure. Rather than make the AERB independent of the DAE, the AEC made the AERB report to itself. Constitutionally, the Secretary of DAE is the ex officio chairman of the AEC. This allows the DAE to exercise administrative powers over the AERB. Till recently, the chairman of the Nuclear Power Corporation was also a member of the AEC. The AERB's budget comes from the DAE. All these factors place structural limits on the AERB's effectiveness. As common experience would indicate, it is hard to criticize one's boss or force action in ways that he or she does not want. This is illustrated by the AERB's inability to force the DAE to carry out its directives on safety tests in the 1990s.[6]

In 2012, the Comptroller and Auditor General assessed the AERB in detail and found legal and practical hurdles in the way of independent functioning of the organization. Noting the implications of the weakness of regulation in Japan for the accidents at Fukushima, CAG warned that 'failure to have an autonomous and empowered regulator is clearly fraught with grave risks' and recommended that the government 'ensure that the nuclear regulator is empowered and independent' (CAG 2012, 9).

There are other ways in which the DAE has marginalized the AERB. In the case of the Kalpakkam Atomic Reprocessing Plant, AERB approval for construction was sought only in 1994 when 'construction of the plant was already in progress' (Sundararajan, Parthasarathy, and Sinha 2008, 26). What, one wonders, were the odds that AERB would disapprove of the project even if it had found a problem with the design?

This administrative control is compounded by the AERB's lack of technical staff and testing facilities. As Gopalakrishnan, former chairman of the AERB, has observed, '95 per cent of the members of the AERB's evaluation committees are scientists and engineers on the payrolls of the DAE. This dependency is deliberately exploited by the DAE management to influence, directly and indirectly, the AERB's safety evaluations and decisions. The interference has manifested itself in the AERB's toning down the seriousness of safety concerns, agreeing to the postponement of essential repairs to suit the DAE's time schedules, and allowing continued operation of installations when public safety considerations would warrant their immediate shutdown and repair' (Gopalakrishnan 1999a).

Neither does the AERB carry out any monitoring of essential performance metrics such as radiological exposure of workers at DAE facilities or measurement of levels of radionuclides in the vicinity of nuclear facilities. These tasks are entrusted to NPCIL or BARC. This state of affairs prompted the Comptroller and Auditor General to criticize the fact that 'AERB had no direct role in conducting independent assessments and monitoring to ensure radiological protection of workers despite being the nuclear regulator of India' (CAG 2012, vii).

Following the Fukushima accidents, in September 2011, the Indian government introduced the Nuclear Safety Regulatory Authority (NSRA) Bill in Parliament to create a new organization that would regulate nuclear activities in the country. The NSRA would replace AERB as the regulator of safety. In March 2012, the bill was reportedly approved by the parliamentary committee on science, technology, environment and forests with minor modifications, though two Communist Party of India (Marxist) members in the panel disagreed with its recommendations and wanted a thorough overhaul of the bill (DHNS 2012).

Looking at the content of the bill and the context under which the NSRA has been created, it seems unlikely to create an effective separation between the regulatory authority and the nuclear establishment. Many of the key processes involved in ensuring effective regulation will continue to be controlled by the AEC. The power for crucial steps like the appointment of members is vested with the Central government. But for most purposes, the authority empowered to act on behalf of the Central government is the AEC. The AEC chairman will also be one of the key members of the Council of Nuclear Safety that will set the policies with respect to radiation and nuclear safety that will fall under the purview of the NSRA. Further, as evidenced by Gopalakrishnan's observation, there is little expertise outside the nuclear establishment on technical issues relating to nuclear facilities.

DESIGN

As I write this in September 2012, in Kalpakkam the DAE is constructing its newest and most heralded reactor—the prototype fast breeder reactor, the first commercial-sized reactor of the second phase of the DAE's much-vaunted three-phase nuclear strategy. DAE scientists 'are confident that the PFBR will be safe and will work efficiently' (Raghotam 2008). The PFBR has a history that stretches back more than a quarter-century and has been designed and redesigned by two generations of DAE engineers and scientists. Its design is thus a good test case to examine how the DAE weighs safety against other priorities.

For a reactor that has been so carefully bred, the PFBR has some serious deficiencies: a design that makes it more susceptible to catastrophic accidents and a containment structure that will not be able to contain the radioactivity released in the event of a severe accident (Kumar and Ramana 2008; Kumar and Ramana 2011). While all nuclear reactors are susceptible to catastrophic accidents, fast reactors pose a unique risk. In fast reactors, the core where the bulk of the nuclear reactions take place is not in its most optimal configuration in terms of energy production when operating normally. If the fuel in the core is rearranged for some reason, it could lead to an increase in the reaction rate and an increase in energy production. This, in turn, could lead to further core rearrangement and a potential positive feedback loop. An example of what is meant by core rearrangement is the localized melting of fuel elements, which is a likely possibility if some part of the core becomes overheated. When the fuel melts, the plutonium and the uranium could flow into those regions of the reactor, closer to other fuel elements. As the fissile materials form a more compact mass, fewer of the neutrons produced during fissions would escape. Then, the rate of fission would increase, causing greater amounts of heat to be produced, in turn causing further fuel elements to melt. The result of this feedback process could be what is called a core disruptive accident (CDA), a core meltdown involving a large and explosive energy release and the potential dispersal of radioactive material into the environment.

The first major study of the energy released by a CDA was done by Nobel Prize-winning physicist H.A. Bethe and British scientist J.H. Tait in 1956 (Bethe and Tait 1956).[7] Since then, estimates of the energy released in a CDA and the ability of the reactor to withstand the accident have been a standard part of the safety evaluations of nearly all of the fast breeder reactors constructed or proposed in the United States and Western Europe (Waltar and Reynolds 1981).

The PFBR also has what is called a positive coolant void coefficient or, a positive sodium void coefficient, because sodium is the material used to carry away the heat produced in the core. This is another positive feedback loop. If some of the molten sodium in the core were to heat up and form bubbles of sodium vapour, the rate of fission reactions, and therefore the heat produced by the reactor, would increase.[8] In turn, this would increase the rate of sodium heating up and forming bubbles. The word 'positive' is because the feedback to the sodium that results from the change in sodium properties causes a greater change in the properties. The word 'void' refers to regions where the sodium might have boiled away.

This positive feedback loop is dangerous and, unless the reactor is immediately shut down, all the sodium could boil away. Because the heat produced would not be taken away by the sodium, the fuel elements in the reactor would start heating up and eventually melting. The magnitude of the void coefficient tends to increase with core size.[9] The fast breeder test reactor, which the DAE has been operating, does not have a positive coolant void coefficient. For the core design that has been adopted for the PFBR, the coolant void coefficient has a value of 4.3 $ ('dollars'), large compared to most commercial breeder reactor designs (IAEA 2006, 48).[10]

Knowing these general facts, my former colleague Ashwin Kumar, an engineer by training, and I looked in more detail at the DAE's studies of potential accidents at the PFBR (Kumar and Ramana 2008). It turns out that the DAE's assertions about the safety of the PFBR are based on the assumption that a CDA will release only 100 megajoules of energy (Chetal et al. 2006, 860). This estimate is much smaller when compared with other fast reactors, especially when the much larger power capacity of the PFBR —and therefore, the larger amount of fissile material used in the reactor—is taken into account. For example, it was estimated that the German SNR-300 reactor, which was designed to produce only 760 megawatts of thermal energy, could produce 370 megajoules in the event of a CDA—much higher than the PFBR estimate. Other fast reactors around the world have similarly higher estimates for how much energy would be produced in such accidents (Waltar and Reynolds 1981, 524).

What Ashwin realized by looking at the DAE's studies was that its estimate is based on two main assumptions: (1) that only part of the core will melt down and contribute to the accident; and (2) that only about 1 per cent of the thermal energy released during the accident would be converted into mechanical energy that could damage the containment building and cause ejection of radioactive materials into the atmosphere (Singh and Harish 2002).

Neither of these assumptions is justifiable. The phenomena that might occur inside the reactor core during a severe accident are very complex (Bell 1981; Wilson 1977), and most studies of breeder accidents assume larger parts of core meltdown in their reference scenarios (Badham and Chan 1979; Jackson and Nicholson 1972; KAERI 1997; Theofanous and Bell 1984). In addition, important omissions of various uncertainties in the parameters used in the DAE's safety studies make its estimate inadequate (Kumar and Ramana 2011). Likewise, the efficiency of conversion could be much larger than the 1 per cent assumed by the DAE. Tests at the British Winfrith facility suggest energy-conversion efficiencies of about 4 per cent (Berthoud 2000).[11] Thus, a severe CDA could release much more energy than the DAE has assumed in its safety analysis.

Finally, if such an accident were to take place, would the PFBR containment—the most visible structure from the outside of any nuclear plant—be able to withstand the shock? The purpose of a containment building is to act as a barrier to the escape of radioactive materials into the atmosphere. Compared to most other breeder reactors, and light water reactors for that matter, the design of the PFBR's containment is relatively weak, only designed to withstand 25 kilopascals of pressure difference (over-pressure) before failing (IAEA 2006, 224; Chetal et al. 2006, 860). Containments for light water reactors routinely have design pressures above 200 kPa (APS Study Group 1985, S94). The design for the 700-MW pressurized heavy water reactors that the DAE is planning to construct includes a containment that is designed to withstand up to 156 kPa (S.A. Bhardwaj 2006, 871). Thus, it is possible to design containments to withstand much higher pressures. The DAE could have chosen such a containment design—and, given the many uncertainties involved, that would have been the safer choice—but did not.

While the DAE could have built a stronger containment, it would also have been possible to decrease the positive void coefficient and, indeed, to make it negative. This could have been done by, for example, designing the reactor core so that fuel subassemblies were interspersed within the depleted uranium blanket, in what is termed a heterogeneous core. The US Clinch River Breeder Reactor, which was eventually cancelled, was designed with a heterogeneous core (Waltar and Reynolds 1981), and Russia has considered a heterogeneous core for its planned BN-1600 reactor (Troyanov et al. 1990). Such a design would have lowered the likelihood of a CDA.

The DAE has defended its choice of a core with a large sodium void coefficient with two arguments. First, and more ironically, it argues that the emphasis on not having a positive sodium void coefficient is mistaken because a 'partial and selective voiding of the core with an overall negative sodium void reactivity effect can still lead to dangerous situations' (Paranjpe 1992, 512). This is puzzling because a similar situation in a core with an overall positive sodium void coefficient can only be more dangerous. The second argument has been that, despite the positive sodium void coefficient, the PFBR is safe because the energy released during the most severe accident can be contained. But, as we have seen, the PFBR's containment may not maintain its integrity during severe accidents.

The DAE, while arguing on the one hand that these safety concerns have been taken into account in the PFBR design, has also argued that safety concerns were completely misplaced in the first place. Thus, S.R. Paranjpe, former director of IGCAR, argued that the fast reactor community ought to ‘assert themselves and destroy the sodium void phobia … the necessity of a dome on the top of the reactor vessel and the core catchers needs to be challenged … after all, if the reactor can be designed to be inherently safe or if the probability of failure of the shutdown function can be brought down to 1e-8 per demand, why invest more funds for safety features’ (Paranjpe 1992, 513).[12]

This statement reveals two reasons why the PFBR has been designed the way it has. First, there is the conviction that the reactor is inherently safe. If one starts with such a conviction, then it is unlikely that safety studies will be reliable (Kumar and Ramana 2011). This conviction is manifested partly through assumptions that cannot really be considered ‘reasonably worst case’.

The second point implied in the same statement (‘why invest more funds’) is that cost has been given a higher priority than safety (Paranjpe 1992, 513). Reducing the sodium coolant void coefficient would have increased the fissile material requirement of the reactor by 30–50 per cent—an expensive component of the initial costs. Likewise, a stronger containment building would have cost more. Another example of where cost comes before safety is the Tarapur I and II reactors that were imported from the United States. These suffered regularly from vibrations, but the DAE chose not to make design and other changes to eliminate them ‘for economic reasons’ (Nanjundeswaran and Sharma 1986, IV-10.8). Now, lowered costs in the case of already-expensive nuclear electricity would be welcome, but not if they come with the increased risk of catastrophic accidents.

EXPERIENCE

The DAE, like other organizations involved in nuclear activities, often verbalizes safety goals. But its performance and decision-making often depart from these public pronouncements. As a way of trying to assess the potential for accidents at Indian nuclear facilities, we turn to three related questions. What has been the experience with accidents, both small and large, at the DAE's facilities? What kind of practices lie beneath the DAE's planning and operations? What has been the DAE's attitude towards nuclear safety?

First, we will discuss some of the major accidents that have occurred in facilities run by the DAE.[13] This is by no means exhaustive and is purely indicative. As argued earlier, the fact that none of these led to catastrophic radioactive release to the environment isn't by itself a source of comfort. Safety theorists have argued cogently that this absence of evidence of 'accidents should never be taken as evidence of the absence of risk …' and that '… just because an operation has not failed catastrophically in the past does not mean it is immune to such failure in the future' (Wolf 2001, 294).

Narora 1993

The most serious of the accidents at nuclear reactors in India occurred on 31 March 1993. Early that morning, two blades of the turbine of the first unit at Narora broke off due to fatigue. They sliced through other blades, destabilizing the turbine and making it vibrate excessively. The vibrations caused the pipes carrying hydrogen gas that cool the turbine to break, releasing the hydrogen, which soon caught fire. Around the same time, lubricant oil too leaked. The fire spread to the oil and throughout the entire turbine building. Among the systems burnt by the fire were four cables that carried wires and electricity, which led to a general blackout in the plant. One set of cables was the one that supplied power to the secondary cooling systems, and when it got burnt those cooling systems were rendered inoperable. To make things worse, the control room was filled with smoke and the operators were forced to leave it about ten minutes after the blade failure.

Prior to leaving, however, the operators manually actuated the primary shutdown system of the reactor (Koley et al. 2006). Fortunately, the reactor shutdown systems worked and control rods were inserted to stop the chain reaction. The problem then was something that was on display at Fukushima: the reactor went on generating heat because the fuel rods in a reactor accumulate fission products which continue to undergo radioactive decay. While this so-called decay heat is only a small fraction of the power that is produced when the reactor is operating at full power, it doesn't stop being produced when the reactor is shut off. It is also significant enough to cause the fuel to get heated up and melt down if ignored, as happened at Fukushima. Thus, the reactor must continue to be cooled even after shutdown. To do this, the operators had to start up diesel-driven fire pumps and circulate *water meant for fire control* to carry away decay heat (NEI 1993).

In addition, there was still concern that the reactor might become critical again. This happens because some of the fission products can absorb neutrons. Therefore, as their concentration changes, the neutron balances change, posing the risk of re-criticality. Therefore, some operators climbed on to the top of the reactor building, with the aid of battery-operated torches, and manually opened valves to release liquid boron into the core, further absorbing neutrons. Had these workers not acted as they did, it is possible, according to the chairman of the AERB, that there would have been a local core-melt and explosive fuel–coolant interaction (Chanda 1999). The names of those heroic workers have never been made public.

It took seventeen hours from the time the fire started for power to be restored to the reactor and its safety systems. The operators who were forced to leave the control room because of smoke could not re-enter it for close to thirteen hours. An attempt was made to control the plant from the emergency control room. But since there was no power available, the Unit 1 control panel of the emergency control room had no functioning indications. Thus, Narora was almost unique in that operators had no indications about the condition of the reactor and were, in effect, 'flying blind' (Nowlen, Kazarians, and Wyant 2001, A23-2).

The Narora accident has been the DAE's closest approach to a catastrophic accident. More worrisome is the evidence that the accident could have been foreseen and prevented.

First, the failure of the turbine blades was avoidable. In 1989, General Electric Company had informed the turbine manufacturer, BHEL, about a design flaw which had led to cracks in similar turbines used around the world. They recommended design modifications, and the manufacturer had responded by preparing detailed drawings for Nuclear Power Corporation, which operated the Narora reactor. However, NPCIL had not taken any action (Gopalakrishnan 1999a). In addition to GE, BHEL had also recommended that NPCIL replace the blade design before any accident occurred. But NPCIL did not act on this advice until months after the accident (Gopalakrishnan 1999b).

Second, even if the turbine blade did fail, the accident might have been averted if the safety systems had been operating which, presumably, they would have if only their power supply had been encased in separate and fire-resistant ducts. By the time the Narora reactor was commissioned, this was established wisdom in the nuclear design community and had been so ever since a fire at Brown's Ferry plant in the United States in 1975. The 1975 accident resulted in significant changes being mandated at all US nuclear plants (Ramsey and Modarres 1998, 106). Nuclear reactor operators had to implement one or more of a number of possible and redundant—physically and electrically—ways of avoiding fire damage. Other countries also adopted similar measures.

Some in the DAE also appear to have been aware of the necessary measures to reduce the risk of fires. The probabilistic safety assessment for Narora performed in 1989 by DAE analysts, including Anil Kakodkar, who was to become head of the DAE in 2000, points out that the effects of common cause failures (described below) would be reduced if 'physical diversity and fire barriers are provided' (Babar et al. 1989). Another paper by safety analysts in the DAE, albeit well after the Narora accident, acknowledges that after 'the Browns Ferry experience in the United States, fire risk evaluation and hazard analysis has been considered as an essential component of safety evaluation and assurance' (Vinod et al. 2008).

Thus, it would seem that even though some sections of the DAE were aware of the risks of a common cause failure in the event of a fire, organizational leaders ignored important safety practices needed to reduce these risks. Instead, the plant was constructed with four backup power supply cables laid in the same duct, without any fire-resistant material enclosing or separating the cable systems. This set-up was perfect for a single cause—a fire—to render these many safety systems inoperable, and constitutes an excellent example of what is called a common cause failure. Such failures are very difficult to predict and model in probabilistic safety assessments (Ramana 2011a).

Third, the DAE had not taken any serious steps towards fire mitigation despite earlier fire accidents at its own reactors.[14] Not only did the fire have precursors, but so did the events that led to the Narora fire. In other words, the factors that contributed to the Narora accident had also been present prior to the accident. This was not something that was discussed in the literature surrounding the Narora accident put out by the DAE. Rather, this realization came about as a result of my colleague Ashwin's looking through the various issues of the IAEA's 'Operating Experience with Nuclear Power Stations in Member States' reports that I had collected over the years.[15]

Let us see the record on two important factors: excessive vibrations in the turbine bearings and oil leaks. In 1981, RAPS I was shut down twice because oil leakage in the turbine building had led to high levels of sparking in the generator exciter (IAEA 1982, 235). After it was restarted, it had to be shut down yet again when it was found that large amounts of oil had leaked from the turbine governing system. Only when the reactor was restarted a third time, in early 1982, were the high vibrations of the turbine bearings noticed and the failure of turbine blades discovered (IAEA 1983, 250). This led to a prolonged shutdown of more than five months; even after this problem had apparently been fixed the reactor had to be shut down once again because of high temperatures in the turbine bearing (IAEA 1983, 250). Again in 1983, high vibrations were noticed in turbine generator bearings and it was revealed that two blades in the second stage of the high-pressure rotor had sheared off at the root (IAEA 1984, 292). In 1985, the first unit of the Madras Atomic Power Station was shut down repeatedly because of high bearing vibrations in the turbine generator (IAEA 1986, 240). RAPS I had to be shut down due to vibrations in the turbine bearing in 1985, 1989 and 1990 (IAEA 1986, 242; 1990, 302; 1991, 298).

Oil leaks have also been common in Indian reactors. In 1988, MAPS II was shut down due to an oil leak from the generator transformer (IAEA 1990, 288). Oil leaked from a turbine bearing in MAPS II in 1989 (IAEA 1990, 300). In 1992, there was an oil leak in the turbine stop valve in MAPS II (IAEA 1993, 288). Additionally, in 1992, there were two separate oil leak incidents in the Narora I turbine generator system (IAEA 1993, 289). There was at least one hydrogen gas leak prior to the Narora accident: this happened in 1991 in the generator stator water system of MAPS II (IAEA 1992, 390).

The DAE did not take serious note of these earlier failures. When asked by an interviewer about recurring turbine blade failures at nuclear reactors, AEC Chairman Chidambaram sidestepped the issue by suggesting that ‘this kind of failure at Narora has happened for the first time … two blades failing’, and then offering the non sequitur, ‘You must remember that as far as nuclear reactor is concerned, there was no problem at Narora. The reactor worked perfectly according to design’ (Chidambaram 1993, 102). By ignoring these early warnings, the DAE set the stage for the Narora failure that led to ‘widespread damage to the [turbine generator] set, condenser and caused [a] fire which engulfed the cables, the turbine building and control equipment room’ (G. Ghosh 1996, 30). But that’s not all. As described later, events such as fires, turbine vibrations, and leaks, have persisted even after the Narora accident, raising questions about what has been learnt from that event.

Kakrapar 1994

One of the actions that the AERB took in the wake of the fire at the Narora plant was to order the DAE to close down other nuclear power stations for inspection of their turbine blades. This may also have prevented an accident at the Kakrapar Atomic Power Station (KAPS). Just behind the turbine building of KAPS is the Moticher Lake; the outlet ducts of the turbine building lead to the lake (Gadekar 1994b). Moticher is an artificial lake and has gates to control the flow of water. However, these gates had not been operated for the most part. As explained by the chief superintendent of KAPS in an interview with *Gujarat Samachar*, mud had ‘collected around [the] gates [and] a lot of tall grass had grown’ near them; therefore, despite a ‘lot of effort the gates of the lake could not be opened’ (Gadekar 1994c, 4).

On 15 and 16 June 1994, there were heavy rains in South Gujarat and the water level of the lake began to rise. That resulted in the ducts that were meant to let out water becoming conduits for water to come in. Water began entering the turbine building on the night of 15 June (Gadekar 1994a).

There were no arrangements either for sealing cable trenches and valve pits, both of which also allowed water to enter the reactor building. By the morning of 16 June, there was water not only in the turbine building but also in other parts of the reactor complex. The workers in the morning shift had to swim in chest-high water, and the control room was reportedly inaccessible for some time (Gadekar 1994a). No action was taken till eleven in the morning on the 16th, when a site emergency was declared and workers were evacuated.

As mentioned, the gates of the Moticher Lake could not be opened, even after the KAPS management requested help from the district and state authorities. Fortunately, villagers from the area, who were worried about the security of their own homes, made a breach in the embankment of the lake which allowed the water to drain out. It was only on 18 June that a large pump was brought to Kakrapar from Tarapur, and the work of removing the water from the turbine building begun (Gadekar 1994a). During all this time, the KAPS management did not think it fit to report to the Atomic Energy Regulatory Board what had happened; the chairman of the Board found out about it from the newspapers (Gadekar 1994c).

Due to floodwater entry, much of the equipment in the turbine building was submerged (Bajaj and Gore 2006). This included the water pumps used to cool the reactor core. Electrical power from the grid failed, and diesel generators had to be used. And finally, some accounts books, correspondence regarding plant construction, and some (engineering) drawings were destroyed (Gadekar 1994c).

Since the reactor had been shut down for over four months at the time of the flooding, there was no great danger of an accident. Had it been functioning and there had been reason to issue an off-site emergency, the situation would have been desperate. In the words of Surendra and Sanghamitra Gadekar: ‘The scene … was one of utter devastation. A thousand houses were demolished in Bardoli alone, and many more elsewhere were damaged. Whole sections of roads, railway lines and bridges vanished into oblivion. Trees were laid low and farms turned into ponds. We were caught 100 km from home and had to trudge back through rivers and streams and making long detours’ (Gadekar 1994b). There was simply no way that people could have been evacuated on time. When the station director was asked how he would have evacuated people if it had become necessary, he said that he would have resorted to the use of helicopters. On being asked how many helicopters did he have access to, he replied that there were two of them. More than 10,000 people were reported to live within just three kilometres of the plant.

As it happened, the main damage resulting from the rains was that the floodwater breached the solid waste–management facility, lifted canisters of radioactive waste and carried them out into the open (Gadekar 1994c). It is not known exactly how many canisters were swept away. Nor is it clear if they were ever recovered or if any of them released its contents into the waters.

Now, none of this would have come to light but for Manoj Mishra. At the time of the accident, he was employed by NPCIL at Kakrapar and was the president of Kakrapar Unit Kendriya Sachivalaya Hindi Parishad (Gujarat High Court 2007). Mishra wrote a letter to *Gujarat Samachar* about what had happened during the flooding. He was suspended and, after an internal inquiry, was removed from service in March 1996. Since then, Mishra has been supporting himself and his family by taking up various odd jobs, and fighting the nuclear establishment in courts—and losing (Gadekar 2010). The most recent, in 2007, was in the Gujarat High Court (Gujarat High Court 2007). Mishra has appealed to the Supreme Court.

The root cause of the Kakrapar flooding—the low elevation of the site—had been identified earlier, and earth supposedly added (M.R. Srinivasan 2002, 139). Clearly, that had proved ineffective. Moreover, the reactor was not well designed: the former head of the AERB has stated that ‘sealing arrangements were not provided to prevent water ingress through cable trenches and valve pits. Similar flooding had occurred twice at RAPS in 1976 and 1982, owing to the very same construction errors as at KAPS’ (Gopalakrishnan 1999a).

Of course, the DAE reassures us that this will never recur and lists various corrective measures it has taken.[16] These would have been reassuring, if only they had included anything that was not obvious—especially at a site that had been determined to be at risk of flooding even before construction started. One would imagine that these measures should have been standard practice long before the first nuclear reactor started operating.

Kaiga 1994

As mentioned in chapter 2, on 13 May 1994, the inner containment dome of one of the units of the Kaiga nuclear power plant collapsed during reactor construction. The dome itself had been completed but cabling and other works were being carried out (Havanur 1994).

Accidents have a way of revealing things that are normally left unsaid. This was the case with the dome collapse, and a number of officials who wished to remain anonymous talked to the media about what went wrong. They revealed at least three of the underlying reasons. The first was inadequate quality control: according to the DAE officials, it seems that 'while inputs, such as, cement and steel, had been tested for quality, that was not the case with the concrete blocks as a whole' (Mohan 1994, 85). This goes against a basic requirement of nuclear safety, which maintains that 'facilities [have to be] constructed to the highest standards' (NEA 1993, 51). Construction workers have accused the contractors of various malpractices in construction (Havanur 1994). Faulty work practices may also have played a role.[17] The second was faulty design (Panneerselvan 1999). Apparently, some cables that run through the dome for prestressing were too closely spaced in certain zones, particularly near the openings for the steam generator, and this caused excessive loading (Sundararajan, Parthasarathy, and Sinha 2008, 41).

The third was a failure of regulation:

> Senior [NPCIL] civil engineers and the private firms which provide civil engineering designs and construction drawings to the DAE have had a close relationship. In this atmosphere of comradeship, the [NPCIL] engineers did not carry out the necessary quality checks on the designs they received before passing them on to the Kaiga project team. The AERB also did not check this, because it had almost no civil engineering staff with it. Serious design errors went undetected and these eventually led to the failure of the dome (Gopalakrishnan 1999b).

The Kaiga dome collapse is unprecedented in the annals of nuclear energy history. It also points to one of the dangers of relying on redundancy as a safety mechanism. The idea behind constructing a containment dome is that even if all safety mechanisms within the reactor fail and a severe accident occurs, the strong containment building will be capable of withstanding the high pressures that would accompany the accident and hold ('contain') all radioactive substances released from the reactor core during the accident. So, at face value, this makes for greater safety. But, consider this speculative scenario:

> If such a collapse had taken place during operation of the nuclear plant, about 130 tonnes of concrete falling from a height of nearly 30 metres would have damaged the automatic control rod drives that lie below the crown of the dome, disabling them and making the safe shutdown of the reactor difficult. The massive weight of concrete might have led to damage to the nuclear coolant pumps and pipes, resulting in severe loss of coolant. This could have led to nuclear core meltdown and the escape of large amounts of radioactive substances to the environment. (Subbarao 1998)

In this admittedly hypothetical scenario, one safety mechanism's failure would have disabled other safety mechanisms and triggered an accident. Fortunately, at the time of the accident, the reactor had not been fully constructed and the core had not been loaded.[18]

The Kaiga episode was also an example of direct interference in the activities of the AERB. According to AERB's Gopalakrishnan, 'When, as chairman, I appointed an independent expert committee to investigate the containment collapse at Kaiga, the AEC chairman wanted its withdrawal and matters left to the committee formed by the [NPCIL] [Managing Director]. DAE also complained to the [Prime Minister's Office] who tried to force me to back off' (Panneerselvan 1999).

Kalpakkam 2003

As described in chapter 4, the Kalpakkam Atomic Reprocessing Plant produces large amounts of chemical and radioactive wastes. Some of this waste is stored in a part of the facility called the Waste Tank Farm (WTF). On 21 January 2003, some employees were tasked with collecting a sample of low-level waste from it. Unknown to them, a valve had failed, resulting in the release of high-level waste, with much higher levels of radioactivity, into that part of the WTF where they were working. Although the plant was five years old, no radiation monitors or mechanisms to detect valve failure had been installed in that area. Therefore, the workers had no way of knowing that the sample they went in to collect was actually emitting high levels of radiation. The accident was recognized only after a sample collected was taken to a different room and processed. In the meantime, six workers had been exposed to high radiation doses (S. Anand 2003).

Apart from the lack of monitoring mechanisms, what is really a cause for concern is the response of the management, in this case, BARC. Despite a safety committee's recommendation that the plant be shut down, the top management of BARC decided to continue operating the plant. Then, the employees' union, the BARC Facilities Employees Association (BFEA), wrote a letter to the director setting forth ten safety-related demands, including the appointment of a full-time safety officer. The letter also recounted two previous incidents in the past two years when workers had been exposed to high levels of radiation, and how the higher officials had always cited emergency as a reason for the Health Physics department not following safety procedures. Once again, there was no response from the management. Finally, some months later, the union resorted to a strike.[19] The management's response was to transfer some of the key workers involved in the agitation and give notice to others; this had the effect desired by the management and, two days later, all the striking workers rejoined. The BARC director's interpretation was: 'If the place was not safe, they would not have joined back'. Finally, the union leaked information about the radiation exposure to the press.

Once the news had become public, the management grudgingly admitted that this was the 'worst accident in radiation exposure in the history of nuclear India' (S. Anand 2003). But it claimed that the 'incident' had resulted from 'over enthusiasm and error of judgment' on the part of the workers (Venkatesh 2003). The management also tried to blame the workers for not wearing their thermoluminescent dosimeter (TLD) badges (Subramanian 2003). But this has nothing to do with the accident: TLD badges would not have warned the workers about radiation levels until well after the fact.[20]

For its part, the BFEA claimed in essence that the accident was only to be expected, and that because of the unrelenting pace of work at KARP and the 'unsafe practices being forced on the workers', accidents have become a regular feature (PTI 2003).

PRACTICES

One can look at safety even in the absence of major accidents, in the failures that occur during day-to-day work in DAE facilities.

Patterns

One feature that points to poor safety practices at DAE facilities is repeated occurrences of similar accidents. An important example is regular leaks and spills of heavy water.[21] Despite a lot of effort—quite understandable because heavy water is expensive and hard to produce—the DAE has not managed to contain them. In 1997, such leaks occurred at the Kakrapar I, MAPS II and Narora II reactors (IAEA 1998, 301–20). The amount of heavy water that leaks can be significant. For example, on 15 April 2000, there was a leak involving seven tonnes of heavy water at the Narora II reactor (AERB 2001, 13). Three years later, on 25 April 2003, there was another heavy water leak at the same reactor, this time involving six tonnes (AERB 2004a, 18). In June and July of 2012, there were two significant heavy water leaks at RAPS, one involving thirty-eight workers being exposed to radioactive tritium (Sundaram 2012; Sebastian 2012a).

The 2003 leak occurred while a device called BARCCIS (Bhabha Atomic Research Centre Channel Inspection System), which is used to inspect coolant tubes in reactors, was in operation. A similar leak had occurred in March 1999 at the Madras Atomic Power Station (described in chapter 8). The Atomic Energy Regulatory Board had undertaken a review of the BARCCIS system and suggested a number of changes in design, operating procedures, and training (AERB 2004a, 18). The occurrence of a similar leak at the Narora reactor despite these changes suggests technical weaknesses in the regulatory board, fundamental flaws in the system, or continued operator errors.

Another set of examples is of the problems that led to the Narora accident. The many instances of problems prior to the accident have already been listed. This trend has continued even after the Narora accident. In late 1993, high vibrations and temperature in both Narora II and RAPS I turbine generator buildings led to their being shut down (IAEA 1994, 333–36). The problems in these reactors persisted into 1994, with Narora II being shut down due to high bearing temperatures, and RAPS I due to turbine bearing vibrations (IAEA 1995, 313–16). In 1995, despite repeated shutdowns supposedly meant to mitigate turbine problems, blades failed in the turbine of Narora II (IAEA 1996, 314).

Even after being restarted following the accident in 1993, Narora I was shut down repeatedly in 1995 because of high vibrations of the turbine generator bearing (IAEA 1996, 312). In 1997, RAPS I had to be repeatedly shut down due to high turbine bearing vibrations (IAEA 1998, 314). In 2000, Kaiga II suffered from repeated turbine vibration problems (IAEA 2001, 294). Fires have also occurred repeatedly. In 1996, in Narora II, there was heavy oil smoke from the turbine building (IAEA 1997, 314). That same year, there was an oil fire in the turbine building of Kalpakkam II (IAEA 1997, 310). The following year, smoke was observed in Kalpakkam II, there was a fire in the turbine generator of Kakrapar II, and smoke was seen coming from the insulation of the main steam line of the turbine generator in Kakrapar II (IAEA 1998, 302–08). There was a fire due to an oil leak in Kalpakkam I in 2000 (IAEA 2001, 300). There have also been numerous oil and hydrogen leaks.[22]

Such repeated problems are indicative of the inability of the organization as a whole to learn appropriate lessons or its inability to control the technology and operate it adequately.

Inoperative Safety Systems

A second notable and disturbing feature is the frequent failure of safety devices. These are the mechanisms by which control of the reactor is sought to be maintained under unanticipated circumstances. Therefore, if they do not work as expected, then, it is more than likely that a small event will cascade into a major accident. A related problem is that of safety devices being left in an inoperative state or of periodic maintenance of equipment being neglected.

An example of how minor failures contribute to escalating an accident is the 1993 Narora accident discussed earlier. The accident could have been prevented had the smoke sensors in the power control room at Narora detected the fire immediately. But that did not happen and the fire was detected only when the flames were noticed by plant personnel (Srinivas 1993). A different complication arose three hours and fifty minutes into the accident when the two operating diesel-driven fire water pumps tripped inexplicably (Nowlen, Kazarians, and Wyant 2001, A23-8). Up to now, the cause for the failure has not been identified. A third pump was out of service for maintenance.

Many of these problems continue to recur. In 2005, for example, the AERB found instances of failures in fire detectors at Kakrapar and in the power supply for emergency cooling at MAPS (PTI 2005).

Another frequent occurrence was heat transport pumps being made unavailable by grid frequency fluctuations. Quite often when this happens, some pumps are already unavailable for use. For example, RAPS I tripped four times in the year 1980, at the time of power system fluctuations, and at least three of these failures were due to the disabling of primary heat transport pumps (IAEA 1981, IN-3, 3). At least once, some of the pumps were already unavailable when this happened. That year, in TAPS II, generation was restricted for nearly two weeks because only one recirculating pump was in service (IAEA 1981, IN-2, 3). Subsequently that year, the unit had to be shut down for twelve days to attend to the failure of the sole recirculating pump.[23] Such problems have occurred repeatedly throughout the 1980s and 1990s.

Similarly in 2004, MAPS II was shut down for eight days because the two main primary coolant pumps were unavailable (IAEA 2005, 324). After being restarted, the reactor had to be shut down again because the motor bearings of one of the pumps had to be replaced. Another example of inadequate maintenance is the response to the leaks of the end shield of RAPS I throughout much of the 1980s.

Emergency Plans

A different perspective on safety practices comes from looking at the design and operation of emergency plans. Though the DAE has argued that nuclear accidents are not possible in India, such plans are typically justified as ‘a measure of abundant caution’ by its personnel (Sundararajan 1991, 389). But, the institution has made these detailed emergency plans inaccessible to the public who should be the real audience for these plans.[24] Independent surveys have observed that panchayat chiefs are often not clear about emergency procedures (MAI 1993, 379). Apart from the culture of secrecy and arrogance characteristic of the nuclear establishment, there are two other plausible reasons. First, publicizing such plans would make people realize that nuclear reactors and other fuel cycle facilities are hazardous. Second, examination of these plans by people outside of the bureaucracy would reveal that they will not work.

An example is the emergency plan for the Kakrapar reactors, which was accidentally made public. The plan was to deal with an estimated 273,843 people who lived within sixteen kilometres of the site (KAPS 1989, 81). The Kakrapar power station is located on the banks of the Tapi River, which had one bridge across it in the vicinity of the reactor. The plan required all evacuees to go over this single bridge, a sure-fire recipe for a major traffic bottleneck (Rawat 1998). The plan also absurdly requires people in villages and towns further up the river to come *towards* the reactor first, cross the bridge and then go away from the reactor. Finally, the plan would try to accommodate 40,000 people in a high-school building and all the residents of Mandvi town and two villages in a primary school in the town of Mangrol.[25]

Emergency plans also demonstrate their propensity for failure during trial exercises—the operational part of our examination. During such drills, officials and local inhabitants are supposed to behave as though a real emergency were under way. But nothing functions the way it should. For example, in 2001, the DAE, along with local officials, carried out an off-site emergency evacuation exercise of villages around MAPS in Kalpakkam. Reflecting, perhaps, the lackadaisical attitude that characterizes safety considerations at nuclear power plants, the station director's wireless set refused to function. Instead, it 'produced just a kee-kee sound' (Radhakrishnan 2001). During an emergency drill in Tarapur in 1988, the collector of Thane district was informed of the 'disaster' at 8.15 p.m. According to the emergency plan, the collector is supposed to immediately proceed to the Emergency Control Room. Instead, he reached at 10.50 a.m. the next morning, and it 'seemed' to observers as if he was 'going about the whole thing as if he was attending just another function where he was asked to perform the role of the chief guest' (Shenoy 1988). In 2012, the Comptroller and Auditor General reported that 'Offsite emergency exercises carried out highlighted inadequate emergency preparedness. Further, AERB was not empowered to secure compliance of corrective measures suggested by it' (CAG 2012, viii).

If emergency plans are so laughably inadequate, why are they even concocted? The best answer comes from sociologist Lee Clarke, who has termed such plans 'fantasy documents', and has argued that these 'are rhetorical instruments that have political utility … for organizations and experts' rather than having any actual use in the event of a real emergency (Clarke 1999, 13). Their purpose is mainly to maintain the legitimacy of the nuclear establishment and allow it to stave off opposition from local inhabitants who are rightly concerned about the potential for catastrophic accidents.

'ABSURD CONFIDENCE'

There is yet another subtle concern with the nuclear establishment's approach to safety. At least from their public persona, the DAE and its attendant organizations are completely confident that the facilities which they build and operate are safe. Following the multiple accidents at Fukushima, the DAE Secretary assured the viewers of the television channel, NDTV, that Indian reactors are 'one hundred percent' safe (Bagla 2011), and that the probability of a nuclear accident is one in infinity, i.e., zero (PTI 2011a).

In fact, the former chairman of the Nuclear Power Corporation has stated that it is 'important' that 'the people (operating the nuclear plant) should be confident about safety' (Subramanian 2000). This suggests that the confident view of safety should not be just a public position—intended to assuage the concerns of the citizenry and the policymakers—but that this confidence should be deeply internalized.

DAE officials routinely exhort employees to be confident of the safety of their operations. An example of this occurred in the aftermath of the 1999 Tokaimura criticality accident in Japan, when newspapers quoted Gopalakrishnan as saying that because 'the degree of automation and cross-checks on safety in our older plants are very minimal … one cannot assert at all that an accident like the one which occurred in Japan will not happen in India' (*Tribune* 1999). This cautionary statement about the risks associated with the technology was too much for the DAE. Delivering the Founder's Day Speech at the annual high-profile special event held at the Bhabha Atomic Research Centre, the AEC chairman responded by saying, ‘such a statement, made without any scientific basis, was a symptom of the technological diffidence in some persons who considered that as a nation, India was not capable of dealing with high technology … I do not think so. And there is no doubt that all of you, who have a spectacular record of achievements, do not think so’ (Chidambaram 1999, 4). Elsewhere, when asked about Gopalakrishnan’s warning by reporters, the AEC chairman categorically asserted that there ‘is no possibility of any nuclear accident in the near or distant future in India. We have 150 safe years of nuclear reactors’ (ToI 1999b).

The extent of the misguided belief that accidents are impossible was apparent in how leaders of the nuclear establishment denied the very nature of what happened at Fukushima. The chairman and managing director of NPCIL claimed: ‘there is no nuclear accident or incident in Japan’s Fukushima plants. It is a well planned emergency preparedness programme which the nuclear operators of the Tokyo Electric Power Company are carrying out to contain the residual heat after the plants had an automatic shutdown following a major earthquake’ (PTI 2011d). The AEC chairman said, ‘It was not a nuclear accident … immediately after the earthquake, the nuclear reactor shut down and nuclear chain reaction stopped’ (PTI 2011a). Such utterances reveal the lengths to which the nuclear establishment goes to maintain its ideology of safety in the face of contrary evidence.

This sort of confidence permeates even the way the DAE characterizes its understanding of the world around it. The DAE’s Reactor Safety Analysis Group had confidently declared in 1986: ‘For coastal sites, flooding may be due to tropical cyclones, tsunamis, seiches and wind waves. In India, tsunamis and seiches do not occur. Hence, cyclones alone have been singled out for detailed study.’ (RSAG 1986, 18). This assertion was belied by the December 2004 tsunami. Though that event has triggered some additional safety features at coastal reactors, it does not seem to have resulted in any introspection within the DAE about how other assumptions that underlie their analyses might prove wrong.

There is a close parallel between a) the way the DAE concluded that just because no tsunamis and seiches had hit India till 1986 that they ‘do not occur’ and b) the way it concluded that since no catastrophic accidents had taken place that its nuclear facilities were safe. The latter simply does not follow from the former. To put it baldly, just because they had not experienced any accident earlier, can one say that the Fukushima Daichi reactors and the Chernobyl reactor were safe before 11 March 2011 and 26 April 1986 respectively? The historical absence of catastrophic accidents cannot be cited as evidence of the absence of *risk* of catastrophic accidents. As in India, ‘many nuclear safety related events occur year after year, all over the world, in all types of nuclear plants and in all reactor designs, and that there are very serious events that go either entirely unnoticed by the broader public or remain significantly under-evaluated when it comes to their potential risk’ (Kastchiev et al. 2007, 95).[26] There have also been many accidents that did not escalate into major ones purely because of chance or the intervention of human operators rather than any technical safety feature. Such factors cannot be taken for granted.

For an organization operating hazardous technologies, being confident that its facilities are not likely to suffer accidents is not conducive to safety. One of the many paradoxes about safety is that ‘if an organization is convinced that it has achieved a safe culture, it almost certainly has not’ (Reason 2000, 4). The pertinence of that observation for the DAE has already been borne out in our examination of the DAE’s operating practices.

In his *Wealth of Nations*, Adam Smith bitingly comments on the search for silver and gold mines: ‘Such in reality is the absurd confidence which almost all men have in their own good fortune, that wherever there is the least probability of success, too great a share of it is apt to go to them of its own accord’ (A. Smith 2001, 742). The statement can well apply, mutatis mutandis, to the DAE’s view of its success in avoiding nuclear accidents.

THEORETICAL PERSPECTIVES

The DAE’s general approach to nuclear safety is typical of how many engineers have thought about the subject, focusing mainly on specific aspects of technology and safety devices. This view has been severely criticized in the scholarly literature following the 1979 Three Mile Island accident, and academics studying safety and safety practitioners have largely moved beyond this framework. In particular, there is widespread recognition that two inherent properties of reactors—‘interactive complexity’ (subsystems interacting in unexpected ways) and ‘tight coupling’ (subsystems having rapid impact on each other)—are serious challenges to ensuring that operations at nuclear reactors are free of accidents (Perrow 1984). Interactive complexity pertains to the potential for hidden and unexpected interactions between different parts of the system, and tight coupling refers to the time-dependence of the system, the presence of strictly prescribed steps, and invariant sequences in operation that cannot be changed. These properties were identified by sociologist Charles Perrow, who also coined the term ‘normal accidents’ to explain that serious accidents appear to be the inevitable consequence of such technologies, regardless of the intent or skill of their designers or operators. Since then, Perrow’s work has spurred an enormous range of analyses on a variety of different systems (Sagan 2004a). According to Perrow, these are inherent features of nuclear reactors and there is a limit to how far they can be reduced through engineering efforts.

From this perspective, there are significant limitations in the way the DAE thinks about safety. First, because of the complexity, the physical conditions that develop during the operation of a reactor may never be fully comprehended, and the understanding that designers or operators have of the reactor would always be partial. Such comprehension might be particularly challenging during accident situations, especially in real time. Second, because of the complexity and short time scales involved, operator actions may not seem erroneous until an ex post facto analysis has been performed. Third, because system components and phenomena could interact in unanticipated ways, it is not possible to predict all possible failure modes.[27] Whether the reactor is safe against unanticipated failures cannot be predicted in advance. An obvious corollary is that numerical estimates of probabilities of catastrophic accidents are uncertain.[28]

Finally, the Normal Accidents School has advanced a very important criticism of a standard method of enhancing safety used by engineers—redundancy. The problem is that redundancy often, if not always, adds to interactive complexity and produces unanticipated problems (Sagan 1993, 2004b). Thus, systems that are added to increase safety might well end up undermining safety in hidden ways. The classic example of this occurred at the Fermi fast breeder reactor in Lagoona Beach, USA, where pieces of zirconium added to the ‘core catcher’—a safety system that is supposed to prevent molten fuel from burning through the reactor vessel—broke off and blocked the entry of liquid sodium into a couple of fuel assemblies. These melted, causing the reactor to shut down (Fuller 1975).

There are also implications for safety from the institutional nature of the DAE. Large bureaucratic organizations exhibit a tendency to downplay the possibility of failures for fear of destroying their reputation and losing their budgets. This is reflected in their not recognizing all possible contingencies and not incorporating adequate safety measures (Rajaraman, Ramana, and Mian 2002). This sense of infallibility is particularly marked in institutions that are characterized by 'expertise' and 'discipline', and further compounded where national security is involved. Political scientist Scott Sagan, in an important and wide-ranging study of several decades of experience with nuclear weapon systems in the United States, points out that in 'total institutions', like a military command, the strong organizational control over members can 'encourage excessive loyalty and secrecy, disdain for outside expertise, and in some cases even cover-ups of safety problems, in order to protect the reputation of the institution' (Sagan 1993, 254). Many, if not all, of these characteristics apply to the DAE.

There is one obvious question that this constellation of hazards—physical and institutional—provokes about nuclear power around the globe: why are there not more accidents? One part of the answer is that, while the nature of the technology implies that there will be failures, there is nothing that determines the rate of failure as such. Therefore, the chances of an accident on any given day may be small but, sooner or later, there will be one. This parallels what happens in a lottery: 'the odds of any given person winning are extremely remote, but the likelihood that *someone* is going to win, sooner or later, is certain' (Chiles 2001, 286).

Another part of the answer has been advanced by the High Reliability Organization (HRO) School, a group of theorists at the University of California, Berkeley. While not dismissing the challenges posed by the structural features identified by Perrow, the HRO theorists tried to explain what allowed some organizations to operate such technological facilities with what they felt was 'an extraordinary level of safety and productive capacity' (La Porte 1996, 60). In other words, their task was to identify the factors that allowed the management of risky technologies with a relative degree of safety. Their search for such explanatory factors primarily focused on intelligent organizational design and good management practices, not technological ones. The HRO Group maintains, though, that they have only uncovered ‘conditions that were *necessary* for relatively safe and productive management of technologies’ but distance themselves from the suggestion or implication that ‘these conditions were *sufficient*’ (La Porte and Rochlin 1994, 225).

The ideal organizations of the HRO theorists have formal structures and clear and consistent goals that ensure reliable operations. The common ingredients that contribute towards the safe operation of hazardous technologies include: political elite and organization leaders placing a high priority on safety in design and operations; setting and maintaining safety standards and practices; ensuring a healthy relationship between management and workers; redundancy in technical operations and personnel management; allowing compensation for failures; and continuous organizational learning via systematic gleaning of feedback (Sagan 1993; La Porte 1996; Bigley and Roberts 2001).

Does the DAE meet with these high standards? The history of accidents and operating practices at the DAE’s facilities outlined here suggests otherwise.[29] In this chapter, we have illustrated it through various examples, including lack of redundancy in safety (KARP),[30] repeated occurrences of avoidable accidents in its facilities, poor organizational learning from previous failures (Narora), questionable construction and manufacturing quality (Kaiga), and the system elite not being sufficiently interested in safety and not being attentive to concerns raised by lower-level staff (KARP). These factors are compounded by an absence of peer-review mechanisms and independent, external oversight.

The lack of high standards of safety is the reason that one cannot take comfort in the fact that, so far, there have not been any catastrophic accidents in India. At the same time, this does not imply that a catastrophic accident will occur tomorrow or in the next month. As safety theorist James Reason argues, ‘Even the most vulnerable systems can evade disaster, at least for a time. Chance does not take sides. It afflicts the deserving and preserves the unworthy’ (Reason 2000). But, if such an accident were to occur, ex post facto analyses are likely to come to the conclusion that, as with Bhopal and Chernobyl, it was an accident waiting to happen.

8

Environment and Health

> *It is indeed true that we live in a society of risky choices, but it is one in which only some do the choosing, while others do the risking.*
>
> —Slavoj Zizek (2010, 13)

Nuclear power poses dangers to the environment and health not just in the event of catastrophic accidents, but also in its day-to-day operations. Different stages of the nuclear fuel chain release radioactive and other toxic materials into the biosphere. These contaminate the areas near various facilities which are involved in producing nuclear electricity or the materials needed to do so. Public concern about such contamination has been increasing, and it has been one factor in generating opposition to new sites for nuclear reactors, uranium mines and potential nuclear waste–disposal sites. As we shall see in this chapter, these concerns do have some justification.

This chapter begins with a discussion of radioactive waste released by the nuclear fuel chain into the environment. In India, the main sources of such releases are uranium mining and milling, and the reprocessing of spent fuel to extract plutonium. The first has been a source of public concern; the latter has not been so widely appreciated. In addition to the potential impact on current populations, a special aspect of radioactive wastes is the long-lived nature of the hazard.

Several epidemiological studies, though none by the nuclear establishment, have demonstrated that there are impacts on the health of people who live in the vicinity of some nuclear facilities and work at some of these facilities. Occupational health is also affected by small incidents at nuclear facilities. Of particular concern is the lot of those temporarily employed by the nuclear establishment, who are reportedly used for many jobs that involve exposure to large radiation doses. If nuclear power is to grow manifold, as the DAE projects, the scale of damage to the environment and health will also naturally rise.

THE ACHILLES HEEL

Radioactive waste is inextricably linked to nuclear energy production. As each nucleus of uranium or plutonium breaks apart to produce power, it also gives rise to radioactive fission products. Other radioactive ‘transuranic elements’ are produced when uranium-238 in the fuel absorbs a neutron—again, an inevitable occurrence in nuclear reactors. Some of these radioactive products have short half-lives, that is, they will be changed into other elements soon, while others have extremely long half-lives, extending in some cases to millions of years. Radioactivity is an inherent property of each isotope and cannot be eliminated through any chemical process. This makes radioactive wastes different from most chemical pollutants that could, at least in principle, be treated and rendered benign.

Since radioactive materials emit ionizing radiation that is hazardous to health (see Box 8.1), this hazard potential of nuclear waste will last as long as some of the constituents remain radioactive, and exposure to these wastes will continue to be harmful. They have to be isolated from human contact and, possibly, monitored if they are not to cause radiation doses. This need for stewardship is unprecedented in human history. It is also clearly iniquitous to future generations since they would have to bear the potential consequences while some in the current generation use the electricity generated by these reactors. The long periods, over which nuclear wastes have to be managed, render conventional cost–benefit analyses untenable because of inherent uncertainties in costs thousands of years into the future and the problems with discounting cash flows over such long periods.

Radioactive waste is generated at various stages of the nuclear fuel chain, which include the mining and milling of uranium ore, fuel fabrication, reactor operation and spent fuel reprocessing (Raj, Prasad, and Bansal 2006) (see Box 8.1 for definitions of the units for radioactive decay). Based on the concentration of radioactivity, these wastes are classified by the DAE into low-level waste (LLW), intermediate-level waste (ILW) and high-level waste (HLW) (DAE 1990).[1] Different wastes are given different classifications depending on whether they are in solid, liquid or gaseous forms and on their production source. For example, in the case of liquid wastes from reprocessing, LLW contains less than 3.7 million Bq/litre of radioactivity, ILW contains between 3.7 million Bq/litre and 370 billion Bq/litre of radioactivity, and HLW contains more than 370 billion Bq/litre of radioactivity (Raj, Prasad, and Bansal 2006, 915). Some wastes are also classified as alpha-contaminated waste and treated separately because of their typically long half-life (Raj, Prasad, and Bansal 2006, 915).

These wastes are dealt with in different ways. For example, the gaseous wastes produced are released through stacks (75–100 m tall) into the environment. While various gas-cleaning techniques are employed (Raj, Prasad, and Bansal 2006, 917), several radionuclides—including tritium, argon-41, and what are called fission product noble gases—do go out into the atmosphere. Similarly, low-level liquid wastes, consisting mostly of tritium but also small quantities of caesium-137 and strontium-90, are released into nearby water bodies after treatment. According to AERB annual reports, the released amounts fluctuate every year and there are significant differences between reactors (for the last published set of figures, see AERB 2011, 51–54). The LLW and the ILW produced by reactors are disposed of in waste-management facilities at the reactor site (Raj, Prasad, and Bansal 2006, 926).

HLW is concentrated by evaporation and stored in stainless steel tanks. These storage tanks require cooling and continuous surveillance (NEA 2005b, 198–205). Eventually, the HLW is to be vitrified, that is, mixed with a molten glassy substance at high temperatures, poured into canisters, and cooled.[2] When solidified, the radionuclides in the HLW will have reduced mobility. However, just like HLW storage tanks, these vitrified waste canisters have to be cooled, because the radioactive decays of fission products continue to give off heat, and there is always the danger that the glass might melt. The glass blocks containing vitrified HLW are kept in the interim Solid Storage Surveillance Facility (S3F) at Tarapur and the plan is to eventually dispose them in a geological storage site. We will discuss that step later.

Waste production is of the most concern at the first and the last steps of this chain: namely, uranium mining and reprocessing. In the first case, the sheer quantities of waste produced are a cause for concern. In the latter case, it is both the large quantity of low-level waste and the small quantity of the very radioactive HLW that are cause for concern.

There are no official estimates of the amount of nuclear waste produced by the nuclear complex, either annually or cumulatively. In 2001, based on the publicly available data, Susy Varughese, a faculty member at the Indian Institute of Technology, Chennai, her student Dennis Thomas, and I estimated the amount of nuclear waste generated by different steps in the nuclear fuel chain (Ramana, Thomas, and Varughese 2001). As of December 2000, the largest volumes were estimated to be those from uranium mining (roughly 4.1 million tonnes, which might occupy approximately 2.6 million cubic m), and LLW from reprocessing (0.21 million cubic m). We estimated that approximately 5000 cubic m of HLW may have been produced till then. These estimates have not been updated so far.

BOX 8.1

RADIATION AND HEALTH

The environment can have an injurious impact on a person's health in two ways: as a source of material toxins (chemical or biological) transferred to the body, and as a source of energy transferred to the body.[3] A specific instance of the latter is radiation. The radiation released by radioactive elements is called ionizing radiation because, upon exposure, it sets free electrons from atoms into the tissues of the body. Other kinds of radiation, for example, microwaves or radio waves, do not have adequate energy to liberate electrons.

The four main kinds of ionizing radiation are beta particles, alpha particles, gamma rays (and X-rays) and neutrons. The last is usually not a concern with nuclear facilities, though it is a source of prompt radiation dose in the case of nuclear explosions. Ionizing radiation effectively causes damage to the body because it delivers its energy in a concentrated manner, thereby breaking chemical bonds. The damage to the DNA (deoxyribonucleic acid) in the cell nucleus is of particular concern.

In the SI system, a radioactive sample decaying at the rate of 1 disintegration per second is defined as having an activity of 1 becquerel (Bq). A more traditional unit for activity, based on the rate of decay of one gm of radium-226, is the curie. One curie (Ci) is defined as the activity of a radionuclide decaying at the rate of 37 billion disintegrations per second. The activity of a radioactive element is inversely proportional to its half-life, the time it takes for half of a certain quantity of the element to decay.

Since the effects of radiation on humans depend on the energy deposited in human tissue, radiation dose is defined in terms of this energy deposition. The SI unit for radiation dose is a gray, which corresponds to the deposition of one joule of energy per kg of tissue. The older unit is a rad, which equals 0.01 gray.

Gamma radiation measurements often use the traditional unit, the roentgen. It is a measure of radiation exposure and is defined as the quantity of radiation (X-rays or gamma rays) that produces a total charge of 258 micro-coulombs of charge (due to ionization) in 1 kg of dry air. It is approximately equal to 0.93 rads for soft body tissue.[4]

The extent of the damage depends on the energy of the incoming radiation and the rate of energy transfer. To capture the latter effect, an empirically determined weighting factor is introduced. Using a reference value of 1 for gamma rays, the weighting factor is 1 for beta rays, 5 to 20 (depending on energy) for neutrons, and 20 for alpha particles. The equivalent dose for biological damage is defined as the absorbed dose times the weighting factor. In SI units, where the absorbed dose is measured in grays, the dose equivalent is measured in sieverts (Sv). The older unit is the rem (for radiation equivalent in man) which corresponds to measuring the absorbed dose in rads. If all this is not confusing enough, what's worse is that too often, the dose equivalent is called the radiation dose; fortunately, what the term refers to is usually clear from the context or from the units used.

There are four possibilities when a radioactive particle or wave hits a cell in the body. First, it may pass through the cell without any damage to the latter; second, it may damage the cell, but the cell does manage to repair the damage before reproducing; third, it may kill the cell; fourth, it may damage the cell in such a way that the damage is passed on when new cells are formed. The third possibility is likely in the case of exposure to very large radiation doses. In that case, a very large number of cells might die, resulting in impaired organ function. In such cases, the deleterious effects of radiation exposure become evident within days or weeks of the exposure, and is often termed acute radiation sickness. Because the evidence of radiation exposure occurs soon after exposure, these effects are considered deterministic—as opposed to stochastic effects, where the symptoms often occur many years after exposure in a probabilistic fashion. Symptoms of acute radiation sickness include vomiting, epilation, haemorrhage, (bloody) diarrhoea and necrotic gingivitis.

The fourth possibility, that is, when cell repair is not perfect and the modification or mutation is transmitted to daughter cells, could result in cancer. However, the occurrence of cancer is stochastic, and predictions can only be made statistically, that is, what fraction of the exposed population will develop symptoms. Whether a specific individual exposed to radiation will develop cancer is not predictable.

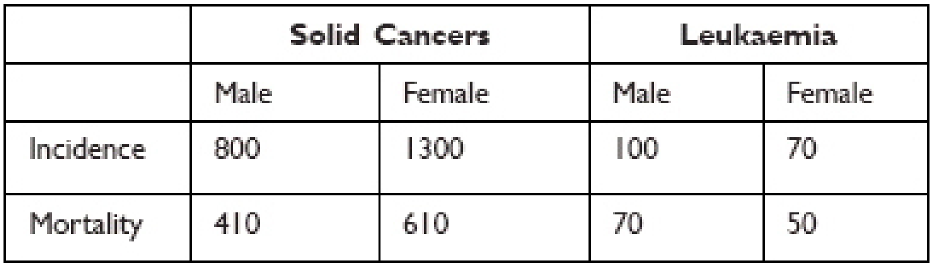
Despite over a half-century of research on health impacts of radiation exposure, the estimation of the probability of developing cancer remains controversial, especially at low doses and low dose rates. The main problem is that these small effects—because they occur against the background of large numbers of incidences of the same end points (cancer, for example) that are not due to radiation exposure—are difficult to detect through epidemiological studies. Therefore, one must extrapolate from high doses.

There is now a considerable amount of theoretical and empirical support for the assumption that the biological risk from radiation exposure is a linear function of radiation dose at low doses.[5] Then, if a given dose is shared among N people, the risk of cancer death per person is reduced to 1/N, but since each of N people now suffers this risk, the total number of cancer deaths that occur remains the same. In other words, dilution is not necessarily an answer to radioactive pollution unless the total radiation dose is reduced.[6]

Much of the radiation and health literature has focused on the risk of cancer. Though of great concern, hereditary effects have so far not been unambiguously detected in human populations, especially in the survivors of the Hiroshima and Nagasaki bombings. Most studies note, however, that experimental studies in plants and animals clearly demonstrate that radiation can induce hereditary effects and that humans are unlikely to be an exception. Other end points that have been related to radiation exposure include strokes, heart disease and various respiratory diseases.

Several international bodies have estimated the lifetime mortality risk per Sv of radiation. According to the most recent report of the US National Academy of Sciences panel on the Biological Effects of Ionizing Radiation, the number of cancer cases and deaths expected to result in 100,000 people (with an age distribution typical of the United States) exposed to 0.1 Sv each are listed in the table below (National Research Council 2006, 15). The risk of cancer is sensitive to age and gender, and children are more susceptible (for example, infants are about four times more at risk than a thirty-year-old).

TABLE 8.1: CANCER INCIDENCE AND MORTALITY ESTIMATES



	Solid Cancers		Leukaemia	
	Male	Female	Male	Female
Incidence	800	1300	100	70
Mortality	410	610	70	50

Note: This is for a cohort exposed to a total radiation dose of 0.1 Sv.

Over the decades, international and national regulatory bodies have come up with radiation standards both as a way of protecting workers and the public, and of establishing legitimacy with the public. In the past, these have been based on shaky science and, over the last century, the recommended annual occupational radiation dose limit has fallen by a factor of about 35 (Inkret, Meinhold, and Taschner 1995, 121). The limit for the public is a factor of 20 lower than the occupational limit.

Uranium Mining

Uranium mining and milling produce huge quantities of alpha-emitting wastes. To start with, the overburden—the rocks that surround the ore vein—has to be dealt with. Like uranium ore, the overburden also contains uranium, though at too low a concentration to be of economic interest. Therefore, it is a source of radon, a gas that is produced when uranium decays spontaneously. The ore, which has higher concentrations of uranium, is milled. During this milling process, the ore is first crushed, ground into small particles and leached into solution using sulphuric acid (Beri 1998, 102). After uranium is precipitated out, the remaining solution, which contains contaminants, including sulphuric acid, heavy metals, nitrates, sulphates, amines and chlorides, is treated to neutralize the acidity and to precipitate radium and other elements resulting from the radioactive decay of uranium. The solid material left over after the uranium has been collected is known as mill tailings.

Tailings are produced in large quantities in uranium milling because the typical amount of uranium in the ore is about 0.1 per cent or less. During the early years of uranium mining in India, on average, the ore contained about 0.067 per cent of uranium oxide (U_3O_8).[7] At this concentration, for each kg of uranium metal produced, over 1750 kg of mill tailings would be left behind. The mining of uranium ore of poorer quality would naturally produce more tailings.

The mill tailings and the effluent from the milling process are disposed of into what are called tailings ponds (Beri 1998, 102). There are three tailings ponds at Jaduguda, the first two of which are now full (Khan et al. 2000, 186). The third tailings pond is currently in use and in May 2009, UCIL proposed expanding its area. These tailings ponds are close to villages and, till a few years ago, were not fenced off to prevent access by people or cattle (Rahman and Basu 1999). The first tailings pond is located only 50 m away from the village of Dungridih and the pipes carrying effluents to the second and third ponds pass just outside the village boundary (Choudhry 2009, 47).

The main radioactive components of mill tailings—thorium-230 and radium-226—have long half-lives, about 75,000 years and 1600 years, respectively (Makhijani, Hu, and Yih 1995, 34). Because the radioactive concentration in mill tailings is low compared to that of most other radioactive wastes, the principal concern is the large volume generated and the long-lived nature of the hazard. They also contain significant quantities of toxic—though non-radioactive—chemicals, including various chlorides, sulphates and heavy metals. In 1999, after thirty years of operation, it was reported that the tailings ponds contained about 6 million tonnes of solid waste containing an estimated radium-226 content of 60 trillion Bq (Basu et al. 1999, 268). These could contaminate nearby water bodies through overflow, especially during monsoons, or seepage into the ground (Krishnamoorthy and Mishra 1999, 31). The radium-226 concentrations in the Gara River at Narwapahar and Jaduguda show significant increases (factors of 2 and 3.7) when upstream and downstream values are compared (Khan et al. 2000, 188).

Due to their fine sandy texture, mill tailings have been used to construct homes and public buildings. Users of these are thereby exposed to gamma radiation and radon. Among the structures reported to be so constructed are the middle school at Jaduguda and the road from Jaduguda to neighbouring Sundar Nagar, about 15 km away (Dias 2007, 146). Authorities did not inform the residents of the risks involved.

Spent Fuel and High-Level Waste

Uranium wastes are a problem because of the huge quantities involved. On the other hand, the spent fuel produced in nuclear reactors and the HLW produced if the spent fuel is reprocessed, although relatively small in quantity, are hazardous because of the high concentration of radioactivity.[8] Since the 1950s, nuclear establishments have looked at different options for dealing with these highly radioactive materials in the long term. In 1957, a report by the US National Academy of Sciences recommended the geologic disposal of radioactive wastes.[9] Such geological repositories are, in essence, holes in appropriate surrounding media to emplace containers with nuclear waste. The major rock types being considered around the world are granite, salt, volcanic tuff and clay, and these differ in their ambient geochemistry, one of the main determinants of the long-term behaviour of radionuclides in the environment if and when water breaches the container with radioactive waste (Ewing 2011, 132–33). In addition, a number of materials have been explored to pack the radioactive materials in, for example, different kinds of glasses and ceramics, and to manufacture containers to store them in, typically of various alloys.

Nevertheless, all these materials are likely to corrode in the presence of water, releasing radioactive materials into the surroundings and, eventually, these could percolate into water bodies. As Allison Macfarlane, chairwoman of the US Nuclear Regulatory Commission, points out, different repositories differ in how long they can ‘prevent the radioactivity from nuclear waste to spread into the accessible environment. In the end, [no] site will [ever] contain nuclear waste indefinitely. The goal is to select a site and engineered features, such as the waste canister, that maximize the amount of time the waste is isolated’ (Macfarlane 2006, 84). The technical problem that has confounded waste disposal in many countries, especially the United States, is the large and unavoidable uncertainties in the characterization of important physical conditions (for example, groundwater flow) at the proposed sites (Macfarlane and Ewing 2006). There are additional uncertainties due to climate change, although these are of secondary importance compared to those related to the long-term behaviour of radionuclides (Swift 1996, 339).

Given these uncertainties and, consequently, the potential risk of radioactive contamination, albeit in the far future, potential sites for nuclear waste disposal have been opposed by the public (Berkhout 1991; von Hippel 2010; Feiveson et al. 2011). During the years when the United States was considering Nevada’s Yucca Mountain as a disposal site for high-level radioactive waste,[10] nationwide surveys showed that a majority of people felt that a repository would reduce the desirability of Nevada as a state to move to, and could deter them from visiting for a vacation or a meeting, a tendency that has been termed stigma (Flynn and Slovic 1995; Gregory, Flynn, and Slovic 1995). When asked to state what images or associations came to mind when they heard the words ‘underground nuclear waste storage facility’, a representative sample of Americans could hardly think of anything that was not frightening or problematic (Slovic 1994).

Those countries that have made any progress in identifying a site for geological waste have realized the importance of public acceptance (Feiveson et al. 2011, 16). They have initiated site selection processes that included significant public stakeholder involvement (NEA 2008a, 8). This has been the case in Canada where the Nuclear Waste Management Organization undertook extensive public consultation over several years; partly due to this process, a few localities have come forward to explore the possibility, albeit somewhat tentatively, of hosting a waste repository (Ramana 2011b, 25–27).

The DAE, on the other hand, has been less than transparent about its efforts at trying to decide on a site for geological waste disposal. In March 1997, the inhabitants of Sanawada village near Pokhran noticed outsiders start drilling the ground in an area near the village. When they asked, the villagers were told that the Mineral Exploration Corporation Ltd (MECL) was drilling for precious stones (Sinha 2000). Later, environmentalists discovered that MECL was doing the drilling for BARC and that Sanawada was being considered as a potential nuclear waste storage location (DTE 2000). Apparently, even the chief minister of Rajasthan did not know of these plans. Thanks to a campaign by local activists, BARC stopped drilling. Shortly afterwards, the junior minister for the Department of Atomic Energy, Vasundhara Raje, said in a written reply to the Rajya Sabha that the government had not taken a decision on the disposal of nuclear wastes, 'as it will take another two decades of research and development to decide on the safest mode and site of disposal' (PTI 2000).

In 2012, AEC Chairman Srikumar Banerjee announced that the DAE had begun looking for a 'rock formation that is geologically stable, totally impervious and without any fissures' to store nuclear waste (PTI 2012a). Nowhere in the announcement was there any mention of consulting with populations living near any such rock formation.

While the high-level waste is at least stored in the hope of finding a permanent burial site, the low-level waste produced during reprocessing is released into the oceans or the atmosphere and is, therefore, a potential source of radioactivity to reach human beings. Traces of these are routinely found in the soil, vegetation, fish, and so on. For example, the levels of iodine-129 in soil samples at a distance of 1.5 km away from the small-sized Trombay reprocessing plant could be nearly fifty times higher than the background levels (Doshi, Joshi, and Pillai 1991, 123).

But, in the case of large reprocessing plants, such contamination can be detected at much greater distances. In 2001, Ireland sued the United Kingdom in the Permanent Court of Arbitration in The Hague to stop the Sellafield complex from discharging radioactive waste into the Irish Sea (PCA 2001).[11] Norway has similarly been concerned about reprocessing in the United Kingdom (NRPA 2002).

As of 2008, the French reprocessing plant, at La Hague, with a nominal capacity of 2000 tonnes of spent fuel every year, was ‘the largest man-made source of radioactivity releases to the environment’ (Schneider and Marignac 2008, 41). One study funded by the European Commission estimated that, on the basis of the average of routine discharges into the ocean and atmosphere between 1999 and 2003, the annual discharges of La Hague would result in a collective dose of 3600 person-Sv which, in turn, would result in about 180 fatal cancer deaths (Smith et al. 2006, 17–19).[12] This is, of course, much lower than what might result from an accident.

PRACTICES

The DAE regularly puts out impressive papers on its radioactive waste handling practices. For example, ‘National Report to the Convention on Nuclear Safety’ declares that ‘radioactive solid wastes are disposed of in brick lined earthen trenches, RCC vaults or tile holes, depending on radioactivity content and radiation levels’ (GoI 2010, 108). This would seem to imply that all radioactive solid waste is safely dealt with. Anecdotal evidence, however, suggests that the actual practices may not be all that safe. For example, UCIL workers had to take their uniforms home and wash them, because no washing facilities were provided on site, thereby exposing their families to radioactive dust (L. Krishnan 2007, 50). The award-winning documentary film *Buddha Weeps in Jaduguda*, for example, has captured on film scenes of leaking casks of uranium yellowcake and tailings being dumped into the Subarnarekha River.[13] UCIL, in response to a petition at the National Environmental Appellate Authority, declared that uranium is systematically packed in drums and properly sealed in the presence of scientists.

Once in a while, the callousness of the authorities comes back to bite them, as it were. On one occasion in the mid-1960s, an underground tank at the Trombay reprocessing plant used for storing irradiated fuel rods became severely contaminated. The water was pumped out into the sea and a very high level of radiation built up close to the shore. What happened after that is best described by Ashok Parthasarathi who was part of the DAE at that point and was to go on to become scientific adviser to the prime minister:

> The next day the canteen waiters of the plutonium plant, who usually used the shore for ablutions, were severely contaminated. Unaware of this, they served in the canteen and passed on the contamination to the technicians who carried it into the labs. Radiation monitors in the labs went haywire due to the very high levels of nuclear radiation they were exposed to. It was only after a great deal of effort that the problem was traced back to the plutonium plant. Thereafter, Health Physics safeguards inside, outside, and around the plutonium plant were stepped up sharply. But [Homi] Sethna (who succeeded Bhabha as AEC Chairman) opposed this continuously. As a result, one of the last office orders [AEC Chairman Homi] Bhabha wrote to A.S. Rao (who was in charge of the Health and Safety Division in BARC) directed him to reassign a certain engineer from the plutonium plant as the latter was being too tough about strict compliance with health and safety practices. Sethna won! (Parthasarathi 2007, 17–18)

A different example comes from the Narora reactor, and was revealed by a member of the nuclear establishment to Surendra Gadekar, editor of *Anumukti* (Sahgal 1998). Once, a worker with a Geiger counter—an instrument used to measure radiation—went to the canteen for tea. His counter suddenly started ticking fast, indicating a high level of radioactivity. On investigating, he found that the radioactivity was coming from the fire on which the tea was being boiled. Further investigation led to the discovery that the wood being burnt in the fire had originally been used for scaffolding inside the plant, and had got contaminated. Instead of being stored as low-level waste, it had been sold to a contractor who, in turn, had sold it to the canteen.

NEIGHBOURHOODS

There have been a few independent epidemiological studies of the health of people living in the vicinity of nuclear facilities. An early study was conducted by the Gandhian group Sampoorna Kranti Vidyalaya (SKV) in the area surrounding the Rajasthan Atomic Power Station. The survey, conducted in 1991, compared the health status of the inhabitants of five villages (total population: 2860) within 10 km of the plant with the corresponding indices for four other villages (total population: 2544) more than 50 km away (Gadekar and Gadekar 1996). The latter villages matched the former villages reasonably well in terms of demographic indicators, such as the age and sex distribution of the population, and the caste composition. This matching is important because rates of several diseases depend on demographic characteristics of the population.

The study observed that there were several statistically significant differences between the two sets of populations. Most striking was the increase in the rate of congenital deformities that was apparent both spatially (that is, more in the proximate than in the control villages) and temporally (that is, more likely for children born after the reactor started operating). Another observed difference was that the proximate villages had a significantly higher rate of spontaneous abortions, stillbirths and of newborn infants who died within a day of their birth. A third difference was a significant increase in the rate of chronic diseases, especially among the young in the proximate villages. However, there was no difference in the rate of acute infections between the two populations. Fourth, there was a higher rate of solid tumours in the nearby villages, and there were more cancer patients and cancer deaths in the villages near the plant.

Likewise, the area near the Jaduguda uranium mines and mills has been studied by some independent groups, in part motivated by numerous anecdotal reports of increased incidences of births with congenital deformities and other undesirable outcomes (Rahman and Basu 1999; M. Tiwari 1999; Sonowal and Jojo 2003). Once again, SKV carried out an epidemiological study in selected villages both near and far from Jaduguda (Gadekar, Shreekumar, and Gadekar 2007). SKV chose four villages near the tailings ponds (see chapter 3) and two villages farther away. Again, the two sets of villages were reasonably well matched in terms of demographic indicators. The only difference was that the people in the nearby villages were wealthier as a result of employment by the Uranium Corporation of India Limited. The employees also had other benefits, such as access to company medical facilities.

The survey team found a discernible difference in the number of congenital deformities among people born after the start of mining operations in 1967. In the villages near the UCIL facility, of the nine children who died within a year of birth, eight had congenital deformities. In the control areas, on the other hand, of the six recorded deaths of children within a year of birth, all were due to infections, such as diarrhea and fever, or premature birth.[14] In the nearby villages, fifty-two men and thirty-four women had deformities, in contrast to just seven of each in the control areas. Evidence of ill health in the vicinity of Jaduguda was also observed in an epidemiological survey carried out by Indian Doctors for Peace and Development (IDPD) in 2007 (Vishnu 2010).

When confronted with such data, the nuclear establishment has a standard set of responses. These range from dismissing the observation entirely ('Congenital malformations occur the world over' [Malhotra 2001]), to finding some alternate explanation ('Illnesses are largely due to malnutrition and an unhealthy lifestyle' [Vishnu 2010]), to invoking scientific studies of radiation effects ('Health effects of radiation have been the subject of detailed study for the past several decades. The United Nations Scientific Committee of the Effects of Atomic Radiation publishes periodic reports on it. None of these ever recorded that radiation can cause such symptoms' [Parthasarathy 2007c]). Occasionally, there is also talk that such claims are made by those who are opposed to India achieving technological progress ('These reports are uninformed and in some cases part of a campaign to stop India from pursuing its nuclear research and power generation,' P.K. Iyengar in *Hindustan Times,* as cited in Gadekar 1993).

Epidemiological surveys cannot reveal the cause of this poor health. However, if a survey is sufficiently well designed—as the ones described here were—they can certainly rule out assertions like the first two. These surveys compare the health indices of two otherwise comparable populations and so, if the population near the nuclear facility has statistically significant excesses of ill health, then, by definition this is different from similar diseases 'everywhere'. Likewise, if nutrition levels of the villages near the nuclear facility are comparable to or better than those of the control villages, as is usually the case, then malnutrition cannot explain the observed health deviation.[15]

One common error on the part of both the nuclear establishment and many journalists and grassroots activists is the assumption that the cause of any ill health can only be radiation exposure.[16] However, in the case of Jaduguda, for example, the impact on public health might just as well have been the result of contamination of drinking water by heavy metals.[17] All that can be plausibly asserted is that whatever is responsible for the observed deformities will be linked to uranium mining, milling or processing, because it is those activities that differentiate the nearby villages from the control villages.

This discussion of what epidemiology can and cannot prove, however, has to be balanced with the words of Mangal Majhi, a member of the Santal tribe involved in uranium surveying: ‘We do not seek a scientific way to prove that we are suffering, that so many of us have diseases we need not have’ (WISE 1993). It reminds us that while the veracity of the effect and the potential cause are being debated, there are real people undergoing enormous hardships.

THE POWER OF STATISTICS

The DAE has published a series of papers that seek to establish that its workers are in good health. One of them examined deaths due to cancer among DAE employees at Tarapur and their family members and found that those risks, whether for employees or their families, were ‘similar to risks experienced by individuals in Bombay’ (Nambi et al. 1992, 155). An earlier analysis of the Trombay facility came to essentially the same conclusion (Nambi, Mayya, and Soman 1991, 61). Finally, a pooled analysis of the records of five units of the Department of Atomic Energy—in Mumbai, Tarapur, Kalpakkam, Hyderabad and Alwaye—also concluded that there was no ‘statistically significant risk of cancer in DAE populations’ when compared to ‘the restricted national base-line data available for cities like Mumbai, Pune and Nagpur’ (Nambi and Mayya 1997, 99).

On the face of it, these studies seem very persuasive, and lead one to think that there is no risk to health from working in radioactive environments. However, there are several problems with these studies. Most important is that the data only included those workers who were still working with the DAE but were not retired employees. No attempt was made to follow employees in later life. Cancer is a disease with a long latency period, and examining subjects without allowing sufficient time for the disease to express itself will give rise to misleading conclusions.

The example of thyroid cancers resulting from the 1986 Chernobyl accident might be useful to recall in this context. In 1991, the International Atomic Energy Agency concluded that ‘there is no clear pathologically documented evidence of an increase in thyroid cancer of the types known to be radiation related' (International Chernobyl Project and International Atomic Energy Agency 1991, 388). Now, the latency period of thyroid cancers from Chernobyl is around 5.8 years (Nikiforov and Gnepp 1994, 748). Trying to assess thyroid cancer incidence before this period has elapsed is therefore likely to suggest that there is no correlation between thyroid cancer incidence and the accident. As time passes, the increased incidence of thyroid cancers becomes more apparent. In 2000, the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) recorded that there were an 'unusually high numbers of thyroid cancers observed in the contaminated areas during the past 14 years', and went on to observe that 'the number of thyroid cancers (about 1,800) in individuals exposed in childhood, in particular in the severely contaminated areas of the three affected countries, is *considerably greater* than expected based on previous knowledge' (UNSCEAR 2000, 504–14) (our emphasis). Similarly, observing DAE workers for longer periods might lead to dramatically different conclusions about their cancer risks.

The second problem is that data on the 'background' rate, that is, the rate in the absence of exposure to radiation in occupational settings, of cancers for Indian populations are sparse and inadequate. Reports produced by cancer registries in India cover less than 5 per cent of the total population of the country (Babu 2009, 1157). Therefore, it could not have been possible for the DAE to find cancer rates in a comparable population without going out itself and undertaking such data collection. Rather than initiate an effort to collect such data, DAE papers use rough estimates from registered cancer cases in some Indian cities. However, these may not be comparable with populations which work in nuclear facilities. Most reactors are located away from cities. In cities, people are exposed to a variety of environmental carcinogens that could increase cancer rates when compared to 'mofussil' or rural populations. The limited amount of data from rural cancer registries indicates that the overall cancer incidence rate in rural India is likely to be much lower than the urban rates (Sankaranarayanan 2008, 161).

In contrast, many studies of nuclear workers in other countries have shown excess risks of cancer, roughly in accordance with estimates of cancer incidence and mortality put out by agencies such as the International Commission on Radiological Protection. The largest study of nuclear workers, carried out by a large team of researchers and headed by a team from the International Agency for Research on Cancer (IARC), retrospectively examined the health records of over 400,000 workers in fifteen countries, and demonstrated that a small excess risk of cancer exists, even at doses lower than typically mandated by radiation standards (Cardis et al. 2005, 77). At the typically mandated radiation standards, workers could receive up to 100 mSv over five years (see, for example, AERB 1992, 7). This would, according to the IARC study, lead to a 9.7 per cent increased mortality from all cancers—excluding leukaemia—and a 19 per cent increased mortality from leukaemia (excluding chronic lymphocytic leukaemia).

This discrepancy between international studies and the DAE's studies is unlikely to be because radiation levels are particularly low at these facilities. Rather, this is likely to be an artefact of poor study design. It may also have to do with the study being carried out by the DAE, whose institutional interests clearly call for making radiation seem more benign than it is. Evidence, even if only suggestive, of such an institutional interest is the difference in evaluations of the health impacts on the inhabitants of the areas with high background radiation in coastal Kerala.[18] Most studies independent of the DAE find significant effects, including Down syndrome and mental retardation (Kochupillai et al. 1976), DNA mutations (Forster et al. 2002) and hereditable anomalies (Padmanabhan et al. 2004). In contrast, most studies involving DAE scientists or DAE funding seem to find no significant impacts (see, for example, Nair et al. 2009).

Some in the DAE have subscribed to a controversial hypothesis called radiation hormesis, which maintains that chronic low doses of radiation are beneficial because they stimulate repair mechanisms. An early paper on the subject argued that the data available on cancer incidence/mortality rates and environmental radiation levels in various cities and states of India substantiate the hypothesis that low levels of ionizing radiations may be beneficial to humans (Nambi and Soman 1987). It also claimed that where the radiation level is greater, the cancer risk is invariably less. These conclusions were based on deficient data and faulty analysis, including the use of only external doses and ignoring the wide variation in internal doses of radiation, and potentially erroneous estimates of cancer incidence for general populations (Makhijani 1987, 1853–55).

There are numerous scientific problems with the hormesis hypothesis, and most scientific bodies that have been constituted specifically to examine the effects of radiation on health have dismissed this hypothesis as not being justified by the available evidence. For example, after examining a large amount of evidence for and against hormesis, the Committee on the Biological Effects of Ionizing Radiation of the US National Research Council concluded that 'the assumption that any stimulatory hormetic effects from low doses of ionizing radiation will have a significant health benefit to humans that exceeds potential detrimental effects from the radiation exposure is unwarranted at this time' (National Research Council 2006, 335).

URANIUM WORKERS

One group of nuclear workers that is expected to suffer deleterious health impacts is uranium miners and millers. Epidemiologic studies of underground miners from around the world have conclusively shown that inhalation of radon—which is naturally generated by radioactive decay in uranium mines—increases the risk of lung cancer; there is supporting evidence from experimental studies on animals and from molecular and cellular studies (BEIR 1988, 1999; UNSCEAR 2000). This body of literature is ignored by the DAE, who have made claims to the contrary. For example, A.N. Mullick, who served as UCIL's chief medical officer for twenty-five years, told a journalist: 'I have not come across any radiation-related ailments during my entire career' (M. Tiwari 1999).

Because the population in the villages near Jaduguda included uranium workers who come directly in contact with uranium (miners, mill workers, casual labourers who load and unload drums of yellowcake on to trains, or the truck drivers who transport uranium ore), the health study conducted by SKV also ended up, willy-nilly, being a study of occupational health.[19] What they found was that a number of people in the vicinity of Jaduguda, mostly uranium workers, suffered from various lung diseases. All had access to medical facilities and many told the SKV surveyors that they had been diagnosed with tuberculosis by the medical authorities. But this tuberculosis did not seem to be responding to standard medication and was chronically present in those people. As part of the survey, those who claimed they had ‘tuberculosis’ were clinically examined by a team of four doctors. Those doctors found that some of the cases had already been cured. On the basis of the remaining cases, the chances of chronic lung problems were worked out to be 4146 per 100,000 amongst uranium workers, 242 per 100,000 amongst non-uranium workers living in nearby villages, and 323 per 100,000 amongst people living in control villages. In other words, the rate of chronic lung problems among uranium workers was more than ten times the corresponding rate among the control population.

The difference between those who lived in the villages near Jaduguda but did not work with uranium and those who lived away from Jaduguda was readily explainable: there is a higher level of prosperity in the proximate villages. Therefore, their nutrition levels were better, and they had larger houses. But as those who carried out the survey point out, ‘the price for their prosperity is paid for by the greater than ten times higher rate amongst the bread-winners. The chances of this anomalously high rate amongst uranium workers being just an inadvertent statistical construct are less than one in a hundred million’ (Gadekar, Shreekumar, and Gadekar 2007).

Though this has not been confirmed by any medical diagnosis, the likely reason for this higher rate of chronic lung disease is silicosis misdiagnosed as tuberculosis. There may also be some cases of lung cancer.[20] This is what one would expect based on the experience of miners around the world (BEIR 1988, 1999; UNSCEAR 2000). A French study, for example, looked at 5086 miners for a mean duration of 30.1 years and found that, while the overall mortality did not differ significantly, there was an excess risk of death due to silicosis and lung cancer; the latter increased with greater exposure to radon (Vacquier et al. 2008, 597).[21]

There is good reason to expect that miners in Jaduguda would have a relatively high incidence of silicosis. Silicosis, a condition involving the scarring and inflammation of the lungs, is caused by exposure to silica dust, which gets embedded deeply in the lungs and cannot be cleared by coughing or through mucous. Silica dust is produced during cutting, breaking, crushing, drilling, grinding or abrasive blasting of rock, and is common in mining.

The level of airborne siliceous dust in mining is subject to limits determined by the Directorate General of Mines Safety (DGMS) (DGMS

1987). The levels of dust in the Jaduguda mines and mills typically fall just below this limit (D.K. Ghosh 1999, 72–73; Kumar and Khan 1999, 133). In some cases, concentrations even exceed the value set by the DGMS; the DAE explains this away by asserting that workers at these locations do not work for more than two to four hours, thereby having annual exposures within the annual limit that can be derived from the concentration prescribed by the DGMS (Kumar and Khan 1999, 132).

However, the limit set by the DGMS is more than one and a half times as high as recommended by the Occupational Safety and Health Administration (OSHA) in the United States (Kretchik 2003). In 2002, the National Institute for Occupational Safety and Health (NIOSH) surveyed a number of health studies and concluded that over a working lifetime (forty to forty-five years) workers have a significant chance (at least 1 in 100) of developing silicosis even at the OSHA permissible exposure limit (NIOSH 2002, v). NIOSH recommended a lower limiting value, which turns out to be several times lower than the value set by the DGMS. Further, the relationship between exposure and risk of developing silicosis appears to be non-linear (Hnizdo and Sluis-Cremer 1993; Finkelstein 2000, 16–17). Even a small increase in dose could lead to a large increase in silicosis incidence. Thus, miners and millers at the DAE's facilities would be at significant risk of developing silicosis at the levels of dust reported by the Health Physics unit of BARC.

The obvious step to be taken is to drastically improve working conditions and to lower ambient dust levels. Studies of uranium miners in Germany show a dramatic reduction in incidence of silicosis (and lung cancer) as working conditions have improved over the years through increased artificial ventilation and the use of wet drilling techniques (Wesch et al. 1999, S49). However, the precondition for such an improvement is acceptance of the possibility of occupational health impacts, rather than the denial that one has witnessed in the DAE's case.

REACTOR WORKERS

In March 1999, some personnel at the second unit of the Madras Atomic Power Station were using the BARCCIS device (Rethinaraj 1999, 52). Suddenly, a plug that sealed one of the coolant channels—through which heavy water was to flow and remove the heat produced during reactor operations—slipped away and a large quantity of radioactive heavy water leaked out. Even though the reactor was shut down for maintenance, a plant emergency was declared. This constituted what nuclear authorities call an incident.

Those who knew about this leak were concerned, and for good reason. Over a period of time, the heavy water loaded in a reactor becomes radioactive because some of the deuterium (heavy hydrogen) nuclei absorb a neutron to become tritium (a hydrogen atom with two neutrons). Further, this tritium will be in the form of tritiated water, which is easily absorbed by the body as it is chemically identical to water. In addition to forming tritiated water, tritium can also displace hydrogen in other types of chemicals, especially organic compounds where it gets bound to carbon. Such organically bound tritium (OBT) remains in the body for long periods of time and, therefore, contributes to a much higher radiation dose per unit of tritium absorbed (Harrison, Khursheed, and Lambert 2002, 300–02).[22] Therefore, the process of cleaning up the spills and recovering the heavy water or flushing it into the environment almost invariably leads to radiation doses to workers and the general public.[23]

The nuclear establishment, which seems to put public relations over public safety, went into a 'deny-and-trivialize' routine. The MAPS director K. Hariharan said: 'We undertook the operation of re-seating the plug in the form of replacement which involves planned escape of heavy water from the channel inside the fuel machine vault' (Subramanian 1999, 28). This made it seem as though no accident had happened and everything had been planned. Hariharan went on to assert that the 'incident … did not involve an *unusual situation*, especially since the unit was under shutdown and the whole activity was planned' (Subramanian 1999, 28) (our emphasis). The leaked heavy water, Hariharan said, was of 'an insignificant quantity' and the amount of radioactive tritium '[released] was well within AERB limits' (Subramanian 1999, 28). All was well, it seemed.

Unfortunately for the nuclear establishment, some people persisted in asking uncomfortable questions. One of them was former AERB chairman Gopalakrishnan who asked, 'Why was a plant emergency declared (during this period, the reactor was shut down)? If the leak was only like that from a tap, why declare a plant emergency?' (Subramanian 1999, 28). He speculated that about 14 tonnes of heavy water might have leaked. In response, the Secretary of AERB, K.S. Parthasarathy, stated that it was less than 4 tonnes (Subramanian 1999, 28). Soon afterwards, the Press Trust of India reported, presumably based on a statement by the Nuclear Power Corporation, that it was about 6 tonnes (Xinhua 1999). Even the lowest of these estimates cannot be considered insignificant. The AERB Secretary also said, reassuringly, that the total (collective) dose to the forty-two workers mobilized in stopping the leak was 0.25 person sievert (Subramanian 1999, 28).

In one sense, the MAPS director's announcement was correct. This accident did not constitute an unusual situation because there have been numerous heavy water leaks in the DAE's reactors.[24] One such accident at MAPS occurred on 5 March 1991 when 0.847 tonnes of heavy water escaped from the moderator system. For once, some details about the leak were revealed by four researchers of the Health Physics Division of the Bhabha Atomic Research Centre in a paper presented at one of the DAE's own conferences (Chudalayandi et al. 1992). Important among the particulars they reported was the fraction of the heavy water that was recovered (41 per cent), and the radioactivity concentration of the air (2.4 GBq/m^3 or billion becquerels per cubic m).[25]

Armed with these parameters, I managed to calculate what radiation doses the exposed workers might have accrued during the clean-up operations (Ramana 1999). Assuming that heavy water from the 1999 spill had been collected with the same efficiency as from the 1991 spill, then, somewhere between 2 and 7 tonnes of heavy water would have been released into the atmosphere through the stack. The radioactivity level would have typically been in the range of 18.5–74 GBq/kg. Thus, somewhere between 37 TBq (terabecquerel or a trillion becquerels) and 518 TBq may have been released. According to the AERB Secretary, 'For the MAPS units, the amount of tritium permitted to be released through the gaseous route is 300 Ci per day per reactor' (Subramanian 1999, 28). Since 300 Ci is equal to 11.1 TBq, it seems quite likely that the amount released that day would have exceeded the daily limit for MAPS II.

The radiation doses to the workers involved in cleaning up the March 1999 spill depends chiefly on the radiation concentration in the spilt heavy water and the length of time the workers were involved in the clean-up; it is essentially independent of the extent of heavy water that is released into the atmosphere. While most of the heavy water would have remained liquid, some portion of it would have evaporated, and workers trying to clean it up would have inhaled it. The amount of water that would have evaporated is determined by the temperature. Just as clothes dry faster on a warm day, the level of vaporization goes up with the temperature. The temperature recorded in Chennai that morning was 36 degrees Celsius and, at that temperature, the heavy water vapour would have had a radioactivity concentration of 1.96 GBq/m^3, assuming a concentration of 37 GBq/m^3 in the heavy water.

Even assuming less than a fifth of this concentration, to account for possible errors, that is, 0.37 GBq/m^3, using standard methods of dose calculation, the radioactive dose to a single worker turns out to be about 6–8 mSv *for each hour of work* (Ramana 1999, 119–20). In 1991, the International Commission on Radiological Protection (ICRP) recommended a limit of 20 mSv per year per worker averaged over five years; in each year, the effective dose should not exceed 30 mSv (ICRP 1991).[26] The AERB's limits for nuclear facilities in India follow these norms (Sundararajan, Parthasarathy, and Sinha 2008, 98–99). Thus, even at the lower limit, an employee working for less than four hours would receive a dose in excess of ICRP recommendations and AERB limits.

If the dose to each of the forty-two workers involved in cleaning up was 6 mSv/h, the collective exposure could be as high as 0.252 sieverts for each hour that they worked. Given the magnitude of the spill, it is likely that 'mopping up' the spill would have taken several hours, if not days. The 1991 spill was cleaned up over a period of four days (5–8 March). Thus, the collective exposure would almost certainly exceed the figure specified by the AERB Secretary.

There is some evidence that corroborates these estimates of radiation doses. Some weeks after the event, workers' union representatives revealed to the press that seven of the workers who helped clean up had been placed in the 'removal category' and would not be allowed to work in any radioactive areas in the future (Radhakrishnan 1999). Most of the remaining workers were placed in the ‘caution category’, meaning that they could continue working but they were not allowed their usual radiation dose.[27]

The reason for discussing this accident at some length is not that the accident was particularly severe, but because it was quite commonplace. Indeed, the official term for this is incident, not accident. Only on rare occasions does the public get to hear of such incident. If and when these incidents do become public, they are usually accompanied by assertions that everything was under control, that there was no danger to the public, and that workers were safe. The analysis of the 1999 MAPS leak suggests that this was not entirely true. The risks to health from such incidents and accidents are in addition to the risks that come from routine operations (such as the risks of silicosis and lung cancer in the case of uranium workers).

Also characteristic in the case of Kalpakkam is a history of poor relations between the management and the workers at both MAPS and KARP. A longstanding problem seems to be one of control over safety at the workplace and outside. For example, in 1997, MAPS workers went on strike for twenty-five days after the management ‘suspended five radiation workers who refused to work in [areas with a] high radiation level’ (HT 1997). One case of workers at KARP going on strike because of safety concerns has been discussed in chapter 7. In 2005, IGCAR employees had threatened to go on strike on account of a number of unfulfilled demands. Among them was that the road from the plant to the housing area be broadened so that the workers would not get stuck in a traffic jam in the event of an emergency (Kalpakkam.com 2005).

The second reason for discussing the Kalpakkam heavy water leak at some length is that such ‘incidents’ could well escalate into major accidents. And very quickly—at Chernobyl, less than ninety seconds elapsed between the first warning that something was wrong and the total destruction of the reactor (Medvedev 1991, 68–77). A common feature in many major accidents is that ‘great events have small beginnings … patient accident reconstruction reveals the banality and triviality behind most catastrophes’ (Perrow 1999, 9). Every accident, small or big, should be treated as a close encounter with disaster.

The Atomic Energy Regulatory Board is fond of claiming that it has lived up to Homi Bhabha's injunction given in February 1960, 'Radioactive materials and sources of radiation should be handled in the Atomic Energy Establishment [the former name of the Bhabha Atomic Research Centre] in a manner which not only ensures that *no harm* can come to workers in the Establishment or anyone else, but also in an exemplary manner, so as to set a standard which other organisations in the country may be asked to emulate' (Mishra 2004, 98) (our emphasis). Clearly, neither in Kalpakkam nor in Jaduguda have nuclear workers been spared from harm.

TEMPORARY WORKERS

In the case of the workers discussed above, they could at least seek recourse through their unions. The lot of the many temporary workers employed by the nuclear establishment is worse. The use of such workers—especially for cleaning tasks in many nuclear facilities—has been reported by many. For example, in connection with the patterns of ill health observed near the Rawatbhata reactor described earlier, Gopalakrishnan pointed out that this may be because 'many villagers in the late 1970s and the late 1980s were used as temporary workers within the power station to clean up radioactive material. There is no database with RAPS about how many people entered the radioactive area or for how long each was exposed to it. As the chairman of the Atomic Energy Regulatory Board, I asked for such information. I never received any' (DTE 1999). The DAE claims that temporary workers have an even lower dose limit (Mishra 2004, 101), but this is refuted by many grassroots and independent accounts of working conditions at nuclear facilities.

For example, in December 1991 an underground pipeline in the CIRUS complex developed a leak and radioactive water leaked out (AERB 1993, 9). According to media sources, the management had 'set six contract labourers on the task of digging a pit, to reach the burst pipeline, eight feet below the surface. These workers wore no protective gear or radiation monitoring badges … The contract labourers who had worked for almost eight hours inside the pit on 13 and 14 December 1991, were thereafter hastily pulled out, given a bath, new sets of clothing and packed off home.

There is no evidence of the labourers having been subject to radiation monitoring tests' (Chinai 1992b).[28]

Another example comes from the Rajasthan Atomic Power Station. 'On 27th of July [1991], there were barrels of heavy water which needed upgrading, standing in a corner of the upgrading plant building. The building was to be whitewashed and a contractor had been assigned the job. One of his labourers, Madholal, who was to do the actual whitewashing found that there was no water in the taps. He made the wash in the barrel of heavy water and then proceeded to put a coat of whitewash on the walls of the room. After finishing his work, Madholal washed his brush and then washed his hands and face with the same heavy water … As soon as information regarding this event reached the authorities, there was consternation and panic amongst them. The new coat of whitewash was scraped off the walls and sent to the laboratory for tritium analysis. Madholal immediately disappeared from the scene and his whereabouts were unknown' (*Rajasthan Patrika* 1991).

High radiation doses to temporary workers seems to have been especially the case at the Tarapur reactors, which was reported in the late 1970s to have areas 'so radioactive that it is impossible for maintenance jobs to be performed without the maintenance personnel exceeding the fortnightly dose … in a matter of minutes' (Bidwai 1978, 29). Because of these many high-radiation areas which had to be serviced, TAPS personnel were 'not capable of handling the larger-than-anticipated volume of maintenance jobs, especially in areas with a large number of hot spots' and so, 'outsiders … [had to be] brought in so as not to overexpose the already highly exposed TAPS personnel to [further] radiation' (Bidwai 1978, 29). Many of these workers did not 'have adequate knowledge or understanding of radiation hazards' nor were they 'entirely familiar either with the layout of TAPS or the precise nature of the job' (Bidwai 1978, 29).[29]

There is plenty of anecdotal evidence along these lines of poor safety practices that possibly result in ill health among workers. The reason that these are mostly anecdotal is that outsiders do not have access to the health records of DAE workers. What little we know is mostly from investigative journalists. Even these journalists, especially those who ask uncomfortable questions, find their access curtailed by the DAE.[30] They are also publicly attacked. For example, on 14 March 1980, there was a leak at the Tarapur nuclear reactor. When this news was reported by journalists, the DAE Secretary Homi Sethna went into ‘a tirade against the press’, describing ‘reporters as “irresponsible”, “self-styled experts”, writing about things on which they lack even “elementary knowledge”’ (K.S. Jayaraman 1980). Again, in 1984, when Praful Bidwai, one of the few journalists with some technical knowledge of nuclear matters, wrote a series of five articles in the *Times of India* pointing out how poorly the DAE’s heavy water production facilities were functioning, the chairman of the AEC at that time, Raja Ramanna, protested to the prime minister and convened a press conference where he publicly termed Bidwai as ‘unpatriotic’, and the publication of the articles, ‘a waste of newsprint’ (Bidwai 1996, 96).

Though nothing concrete can be established in such matters, one cannot but wonder if the relationship of senior DAE bureaucrats to radiation protection is somehow emblematic of their larger relationship to the masses in the country. In a fascinating analysis of AEC Chairman Raja Ramanna’s autobiography, Sankaran Krishna has identified how the scientist views the ‘excessive numbers of people in India’ as a major problem (Krishna 2006, 2331). It is, of course, possible that one could combine a concern about the population of the country imposing a strain on the resources with respect for each individual and their health. But, then again, consider a speech by Homi Bhabha to a conference on population and planned parenthood in 1959. Reducing the ‘population problem’ to a purely statistical one, where the number of births exceeded the number of deaths, Bhabha called for scientists to develop some substance that would reduce the probability of conception (Bhabha 1989, 33). Once such a substance was found, Bhabha advocated mixing it with some staple ingredient of ‘one’s daily diet such as rice, grain, or salt’. He expressed no ethical qualms about, for example, whether it might deny a couple, who already have trouble conceiving children, the chance to have any offspring. Or that, in a democracy, some notion of informed consent should be involved before subjecting people to such adulteration of their basic food.

On 24 December 2006, when a pipe that carried radioactive waste from a Uranium Corporation plant to a storage dam burst in the vicinity of Dungridih village, the authorities were nowhere to be seen (L. Krishnan 2007, 50). Only after angry villagers went and complained at the UCIL plant did the management even come to know about this leak. Sludge kept escaping into a rivulet for nine hours, killing fish and affecting nearby and downstream communities that depend on the watershed for both fishing and irrigation. Similar leaks were to occur on at least three more occasions over the next couple of years (A. Tiwari 2008). On the last occasion, the UCIL chairman said, 'The leakage, caused due to dislocation of a rubber flange, was minimum and there is nothing to worry about. Since the incident has taken place third time in a year on the same spot, we have decided to probe the issue' (*Telegraph* 2008).

That the same kind of event could happen three times on the same spot shows that, despite the nuclear establishment claiming that it cares about the environment, it does not take adequate precautions. But, one could go further and examine how serious the DAE is about monitoring the environment. For example, two papers (Bhat et al. 1991, 534; Chandrasekharan et al. 1992, 19) state how much gaseous argon-41 was released from the Madras Atomic Power Station in 1990; however, these numbers vary by 37.5 per cent; there is even one scientist (M.A.R. Iyengar) who was one of the authors of both papers. This discrepancy suggests that measurements of radioactive gases were not carried out or reported with care.

As with releases, so, too, with estimates of radiation dose to exposed individuals. In May 1998, tritiated heavy water with levels of tritium above the limits set by the AERB was released from RAPS II into the Rana Pratap Sagar Lake; the release was due to a leak in the moderator heat exchanger (PTI 1999). However, this event was not revealed to the general public or the local inhabitants till December 1999, when the junior minister for atomic energy told Parliament about the leak (AFP 1999). Not surprisingly, the announcement was followed by the usual 'there was no danger to the population' disclaimer.

But was this in fact true? According to Gopalakrishnan the official estimates of radiation doses to people were based on the assumption that the released activity had perfectly mixed with the 'entire body' of water in the lake, but ‘this never happens for several weeks and the concentration of radioactivity in the lake region close to the exit point of the leak will contain tens of times of more radioactivity for quite some time. People who had drunk water or eaten fish from the lake must have ingested considerably more radioactivity than what the DAE would like the Minister and the Parliament to believe’ (*Hindu* 1999). Had the local people been warned in advance, they would at least have avoided using the water or eating fish from the lake for a period of time.

A problem that is far more serious than carelessness is the complete lack of accountability. The inability to hold the nuclear establishment accountable has been described in other chapters as well, in particular, chapters 5 and 6. Within the context of environment and health, even though there have been several revelations of radiation leaks, safety errors, and workers being subjected to high levels of radiation, none of these has resulted in the DAE’s being forced to undertake any major policy changes. By and large, the regulatory authorities, that is, the Atomic Energy Regulatory Board and the pollution control boards, have been more concerned about keeping nuclear facilities operational than about public health. So far, no reactors have been shut down for exceeding radiation limits in effluents. None of these issues has been subject to any meaningful debates in Parliament or the Legislative Assemblies.

Unlike most policy matters where the cabinet has the ultimate authority, the DAE was set up in 1954 under the direct charge of the prime minister. This structure makes it difficult for most politicians or bureaucrats—let alone commoners—to challenge the DAE’s policies or practices. As the well-known politician, Jayanthi Natarajan, was to despair publicly:

> I have been a Member of the Parliamentary Consultative Committee for Defence and Atomic Energy, and have tried time and again to raise issues relating to public safety, both at Parliamentary Committee hearings, and in the Rajya Sabha, and have achieved precious little for my pains. Since I was an MP at the time, and a pretty aggressive one, I had to be dealt with. But they simply drowned me with totally obscure and incomprehensible scientific terms and explanations, which sounded impressive, and meant nothing. The rest was simply not forthcoming because they claimed it was ‘classified’. I have repeatedly raised the issue of the hazards of radiation leaks, safety procedures, and environmental contamination, that might flow from the atomic power station at Kalpakkam, but have always received the bland and meaningless reply that the radiation was ‘within acceptable limits’. (Natarajan 2003)

Time and again, members of the government of the day, regardless of party affiliations, have shut off debate on various critical aspects of nuclear power in legislatures and Parliament.[31] All in all, the larger institutional structure under which the DAE operates allows it to evade parliamentary checks and balances.

HAZARDS AND HARM

In the last decade, taking advantage of public concern about global warming, nuclear establishments around the world have tried to represent nuclear power as an environmentally sustainable source of electricity. The DAE is no exception. For example, the 'Declaration by India and France on the Development of Nuclear Energy for Peaceful Purposes' signed in February 2006 begins with the 'recognition' that 'nuclear energy provides a safe, environment-friendly and sustainable source of energy'.

There is a reason why the nuclear establishment needs to keep representing nuclear power as environmentally desirable. In 1994, the Kroc Institute for International Peace Studies, University of Notre Dame, conducted one of the few detailed surveys of public opinion on nuclear issues in India. The survey included nearly 1000 persons, all living in large urban areas, the majority of whom were 'middle and upper class men,' that is, members of the elite that has historically been supportive of nuclear power. Among them, nearly 60 per cent felt that a 'civilian nuclear energy programme has high environmental costs attached', even though the same percentage also felt that nuclear power was beneficial (Cortright and Mattoo 1996, 116).[32] In other words, even those who support nuclear power in general do not seem to think of nuclear power as environmentally desirable. This is obviously a problem for nuclear advocates.

The portrayal of nuclear power as environmentally friendly is particularly ironical since there is as yet no credible solution to the environmental problem that has been the source of much public concern: that of radioactive waste, which remains hazardous for millennia. Different kinds of radioactive wastes are produced at every stage of the nuclear fuel chain. They have contaminated drinking water, polluted the air and increased the radioactivity levels of soil, the flora and the fauna in various parts of the world. Thus, producing nuclear power is also environmentally hazardous, albeit in a different way from burning fossil fuels, and a nuclear future merely trades radioactive externalities for carbon emissions at best. There is also the under-examined question of toxic materials used in the nuclear fuel chain. Expanding the scale of nuclear energy generation, in India or elsewhere, will only expand the scale of pollution and environmental damage.

All this is not meant to imply that the DAE intends to harm the environment or people's or workers' health. But, as documented here, there is ample evidence, even though much of it is necessarily anecdotal, that such harm does result from their activities. As the poet T.S. Eliot put it in *The Cocktail Party*, 'Half the harm that is done in this world is due to people who want to feel important. They don't mean to do harm; but the harm does not interest them' (Eliot 1974, 111).

Conclusion

> *The basic issues in the nuclear controversy are simple in essence and are the very same issues* [*as*] *those of freedom, equity, social justice, vulnerability,* [*and*] *bureaucratized high technology which confront us in all other facets of 'development'.*
>
> —Surendra Gadekar (1987a, 1)

We return to the first of the two questions we started the book with: Is a rapid and large-scale expansion of nuclear power in India, along the lines projected by the DAE, feasible? The answer that emerges in the course of our excursion through the history of how the nuclear project has materialized in the country is that it is very unlikely and probably impossible. The principal reasons, among many, for this conclusion are the technical implausibility of the DAE's plans, its inability as an organization to learn lessons from its earlier failures, and local opposition.

Slow Growth of the Fast Breeder

Over the course of the book, we have seen why various components of the nuclear establishment's plans have serious flaws. The most important of these is that the DAE's projections have simply not accounted properly for the future availability of plutonium. The basic error has to do with an improper methodology as discussed in chapter 4. As a result, the growth rates projected by the DAE are but plain impossibilities. In addition, the DAE has resorted to various unrealistic assumptions about dealing with radioactive spent fuel and about recovering plutonium.

The mere fact that the DAE has chosen to base its plans on fast breeder reactors—a technology shown in so many different countries to be unreliable—makes it unlikely that nuclear power will ever become a major source of electricity in India. Up to the 1970s, many countries had made similar plans involving breeder reactor construction. These plans were motivated by the widespread misconception that the availability of uranium globally would be a major limitation on nuclear power, the assumption that nuclear power (and energy consumption in general) would grow far more rapidly than has turned out to be the case, and the optimistic assumption that breeder reactors would be easy to construct and operate. Many of these countries spent the equivalent of tens of billions of dollars constructing prototype breeder reactors but, over the last couple of decades, efforts to commercialize them have been steadily cut back, if not abandoned, in most countries (IPFM 2010a).[1]

None of the assumptions motivating breeders has proved true. In 1975, two analysts from the International Atomic Energy Agency had projected that, by 2000, the global nuclear generation capacity would be between 3600 GW (reference case) and 5300 GW (accelerated case), representing 40 to 60 per cent of total electrical capacity (Goodman and Krymm 1975, 12–13). Contrast this with the situation in 2010, before the Fukushima accidents, when the global nuclear capacity was about 375 GW and constituted 7.4 per cent of electrical generation capacity (IAEA 2011, 17).[2] The 2011 report on 'The Future of the Nuclear Fuel Cycle' from the Massachusetts Institute of Technology argued that there was 'no shortage of uranium resources that might constrain future commitments to build new nuclear plants for much of this century at least' (Kazimi, Moniz, and Forsberg 2011, x). That the DAE has chosen to stick with a plan chalked out in the 1950s, and not revise it on the basis of new knowledge, raises grave doubts about the organization's learning capacity.

Lessons Not Learnt

The inability of the nuclear establishment—and governments that support them—to learn lessons from earlier experiences is also apparent in their assumptions about how long reactors and other facilities would take to be constructed. At the time of writing this, the most recent illustration of this was provided in a written reply in the Lok Sabha by V. Narayanasamy of the Prime Minister's Office, which states that the plan is 'to reach 10,080 MW by 2017' but then goes on to stating that the 'XII Five Year Plan envisages start of work on nuclear power reactors adding to total an additional capacity of 17400 MW. This additional planned capacity makes it total to 27480 MW by the year 2023-24' (Narayanasamy 2012b). The

2017 target is clearly a comedown from earlier plans to reach 20,000 MW by 2020.

The second implicit assumption is that if work is started on 17,400 MW, then all those reactors will be completed within a few years. In chapter 2, we have seen that there were unanticipated problems in reactor after reactor, delaying the commencement of operations at these facilities. This is despite the fact that most of the reactors constructed so far are essentially of the same design as the RAPS I reactor imported from Canada. Current plans envisage importing a variety of new reactor designs from international vendors like Areva and Westinghouse, and one may expect more delays. Unfortunately, there is no place for such delays in the DAE's facile plans for rapid deployment of nuclear reactors. For example, in the forecasts that AEC Chairman Kakodkar used as justification for importing LWRs through the US–India deal, the DAE envisions commissioning thirty-five large nuclear reactors—roughly 35,000 MW—*every year* on average in the decade from 2040 to 2050 (Kakodkar 2008). The implicit assumption in such forecasts is that the set of potential problems has been exhausted and that the future will be completely smooth.

A recurring problem, which is bound to intensify in the future, is the opposition faced during the process of acquiring new sites for the many nuclear facilities that would accompany a large-scale expansion of nuclear power. Such opposition started in the 1980s and has been building up steadily. This has resulted in at least a few defeats for the DAE, including most decisively at two sites in Kerala, setbacks in plans to construct reactors in West Bengal, and to mine uranium in Meghalaya. In the past, the sheer political power of the DAE and the State resources that it can command—including the police and various district administrative officials—have gotten the better of the protesters. But this is getting harder. At the very minimum, such protests can considerably slow down construction. Therefore, even if the opposition to reactors and other facilities does not translate into a cessation of nuclear construction, it can make it impossible for nuclear capacity to grow rapidly in the country.[3]

Another aspect of the past that the nuclear establishment has ignored is the history of reactors that cost more than was forecast. This is even more inexplicable in the case of breeder reactors in view of the serious problems with that technology. Though the PFBR went up in cost by over 60 per cent, the DAE continues to believe that future breeder reactors will be cheaper; indeed, for the next set of FBRs, IGCAR projects a reduction in tariff by 35 per cent (Chetal et al. 2011, 69). For imported reactors, in order to make them seem competitive with other sources of power and thus justify purchasing them, NPCIL has assumed absurdly high reductions in construction costs as compared to Western Europe and the US. These projected costs are very unlikely to materialize.

For these primary reasons, nuclear power can, at best, increase slowly and continue to contribute relatively low proportions of India's electricity in the coming decades. We now turn to the second of the questions we started with: is it desirable to expand nuclear power on a large scale? An answer to this question necessarily has to be more nuanced, and we explore some of these nuances below.

THE GOOD, THE BAD AND THE UGLY

The strongest argument for nuclear energy is that it is technically feasible to generate large amounts of it, even if this may not happen at the rapid rates of expansion claimed by the nuclear industry. There seems to be ample uranium in the world, sufficient to fuel reactors based on currently popular designs, for many decades, even in the face of major nuclear expansion (Kazimi, Moniz, and Forsberg 2011; Schneider and Sailor 2008).[4] How much uranium is under the ground in India is an unsettled question, and the answer will change with time as resource exploration continues. But since India is no longer prohibited from importing uranium, the domestic availability is not a key issue. Thus, in principle, nuclear energy can be expanded significantly without running into fuel constraints.

This ability to promise to produce large amounts of energy has been one of the two pillars of the DAE's institutional and political power. The attractiveness of this characteristic is that it serves the interests of the elite who are looking to unbridled consumption requiring ever-increasing amounts of energy. As we saw in chapter 1, the nuclear establishment has offered a series of ambitious projections, none of which has come close to being fulfilled. Over the decades, such promises of large quantities of electricity generation, sometime far in the future, have allowed the DAE to attract high levels of funding despite its many failures.

Some other sources of power—solar energy in particular—also have the potential to generate vast amounts of energy without running into fuel constraints. But none of these possesses nuclear power's second significant characteristic—the ability to produce the means to manufacture weapons of mass murder. This characteristic is the second pillar of the nuclear establishment's political and institutional power. Again, this is attractive to the elite, and public opinion surveys have attested to the popularity of the bomb amongst the elite in India (Cortright and Mattoo 1996).

Public opinion surveys also provide evidence of support for the goal of global nuclear disarmament, and this brings us to one of the undesirable features of nuclear power: its intrinsic and possibly inextricable relationship with the capacity to make nuclear weapons. In the words of Ted Taylor (2005), a former weapons designer turned nuclear abolition advocate, 'the connections between nuclear technology for constructive use and for destructive use are so closely tied together that the benefits of the one are not accessible without greatly increasing the hazards of the other' (124).

There are two primary reasons for the overlap. The first is that all nuclear reactors produce weapons-usable plutonium. Similarly, facilities for the enrichment of uranium for use in light water reactors can also be used to produce weapons-usable highly enriched uranium (HEU). In general, many of the physical steps involved in nuclear energy production and nuclear weapons production are the same, and the infrastructure for one can contribute substantially to the other. Second, as part of a nuclear energy programme, people have to be trained in various aspects of nuclear physics and technology. These people can then apply the same skills to nuclear weapons research and development. The DAE's trajectory—from an organization intended to develop atomic energy for peaceful purposes to the purveyors of a nuclear arsenal offering multiple weapons designs—offers a striking illustration of this reality (Ramana 2003). Making nuclear weapons, therefore, would become a matter of choice, not of capability. A nuclear-powered future makes nuclear disarmament intrinsically unstable.

This ability to produce nuclear weapons allows the DAE to offer something that no other energy technology offers, and the resultant political power has been used by the DAE to bypass democracy. On many occasions, the DAE has resorted to the argument that, due to national security considerations, it cannot be held accountable by various organs of the government. This has been true not just in India but in many other countries, and constitutes another unattractive feature of nuclear power. The impossibility of subjecting nuclear weapons to democratic control has been described by political theorist Langdon Winner (1986, 34): ‘As long as it exists at all, its lethal properties demand that it be controlled by a centralized, rigidly hierarchical chain of command closed to all influences that might make its workings unpredictable. The internal social system of the bomb must be authoritarian; there is no other way.’ To be sure, nuclear power is not the only undemocratic technology. But because of its exalted status in elite imagination and its link to the bomb, it succeeds in this task better than most other technologies aspiring to this position.

We now turn to another of the negative characteristics of nuclear power—its economic costs. Should there be an expansion of nuclear power in the country, even if not on the scale envisioned by the DAE, there would be significant costs, not all of which may be fully accounted for. As we discussed in chapter 6, nuclear power has been an expensive way of generating electricity. The Nuclear Power Corporation has tried to make it seem competitive through creative accounting and the subsidies provided by the government through the DAE. An example is discussed in chapter 5. As in the past, the nuclear establishment projects that future reactors will be cheap. Just as with construction time estimates, such cost estimates implicitly assume that all previous problems have been solved and no new problems will ever emerge.[5] Such assumptions have been repeatedly shown to be untenable as reactor after reactor has experienced cost overruns.

Expectations that the nuclear industry will learn from past experience and lower the construction costs have also been belied repeatedly. Nuclear reactor costs have risen steadily in many countries, and this has been best documented in cases of the United States and France (Koomey and Hultman 2007; Grubler 2009). Indeed, there are good reasons why technological learning in nuclear power can be very slow, at best. The relatively long lead times for construction and commissioning means that improvements derived by feeding back information from operating and design experiences with early units are necessarily slow. The large size of a nuclear reactor offers a lower scope for reduction of cost through modular manufacture as compared to, say, renewable energy technologies. The lower the learning rate, the higher the costs of technology maturing and the greater the levels of investment required to make the technology economical (McDonald and Schrattenholzer 2001, 256).

The high upfront capital cost and the long construction period tie up large amounts of capital with no economic returns for an extended period of time. Since this capital could be used more profitably elsewhere within the power sector, investment in nuclear power imposes significant opportunity costs. For the same reason, considerable government subsidies and other forms of intervention are needed to induce the private sector to participate in the nuclear power sector.

An example of government intervention designed to attract private investment in the building and operating of nuclear reactors is the nuclear liability bill passed in the Indian Parliament in 2010. The legislation capped the liability of the operator of a nuclear reactor at a value that is quite low compared to the cost of dealing with a catastrophic accident. Corporate entities had been demanding such legislation even earlier. For example, in his 23 September 2008 statement as chairman of Reliance Power, Anil Ambani explicitly stated that they expected the government to ‘make at least 15 other policy changes to permit the entry of private players into the nuclear domain’, including ‘enacting national legislations on civil liabilities’ (Ambani 2008). Although private participation is currently disallowed—except, potentially, as project partners with NPCIL holding the majority stake—this might change in the future.

Another unattractive feature of nuclear power is that it poses risks to public health and the environment. These risks are significant enough in the eyes of many members of the public so that there is widespread opposition to the construction of these facilities in most parts of the world. These risks arise both due to the potential for catastrophic accidents in nuclear reactors, which was discussed in [6] Elevated levels of fission products such as iodine-131 and caesium-137 were detected in air, water and milk samples collected from across the United States between 17 March and 4 April 2011 as a result of the multiple accidents in Fukushima (Thakur, Ballard, and Nelson 2012). Studies of annual radiation doses that people are exposed to in areas contaminated with high levels of fallout from the Chernobyl accident show only slow rates of decline (Bernhardsson et al. 2011).

Despite decades of research and development, these risks have not been eliminated, and there are good theoretical and empirical grounds to believe that they cannot ever be eliminated. Attempts to lower the risk makes the construction of nuclear facilities more expensive, thus accentuating the problem mentioned earlier—that of high fixed costs. These higher costs are primarily due to the need to put safety systems that might reduce the potential for, or the consequences of, accidents, and the installation of devices to capture dangerous radionuclides. One reflection of the nuclear industry's implicit acceptance of the reality of the risk of a catastrophic accident is its effort to limit the liability of private vendors and operators in the event of a disaster. Because of its political clout, it has succeeded in this effort and the government has in effect transferred a part of the financial risk associated with constructing and operating nuclear reactors to the citizenry at large.

The non-financial risks to health and environment are unequally distributed, with communities living in the vicinity of nuclear facilities bearing a predominant part of these risks. These communities have had no say in the siting, construction or operational practices of the nuclear facilities that have come to dominate their lives in various ways. This disproportionate arrangement is one reason for their opposition. We discuss this in greater detail below.

Putting all these—the good, the bad and the ugly—together, my personal answer to the question of desirability is in the negative.

NUCLEAR POWER AND CLIMATE CHANGE

The recent interest in nuclear power around the world has been motivated partly because nuclear power is less carbon-intensive than fossil fuels. Therefore, given the gravity of the climate danger, there is an additional motivation to *consider* a large-scale expansion of nuclear power around the world.

Saying that, however, is not the same as saying nuclear power is a solution to climate change. As energy analyst Arjun Makhijani has argued (2006), 'The central problem is not the technical feasibility because there are many possible ways to create a low carbon dioxide energy system. The crucial questions lie in the costs and consequences of using different technologies to overcome the problem of CO_2 emissions.’ In the case of nuclear technology, these costs and consequences, especially for India, have been elaborated at length in this book.

For nuclear power to contribute significantly to climate-change mitigation, it would have to grow from the current 375 GW to roughly double that figure by around 2050 if it is to even reduce the anticipated *increase* in emissions in business as usual (BAU) scenarios by about an eighth (Pacala and Socolow 2004). This involves constructing a very large number of reactors, many of which would have to be in countries around the world that have fast rates of electricity demand growth but have little or no experience with constructing or operating nuclear reactors. This includes countries that are considered ‘politically unstable’. Underscoring the importance of such countries, physicists and energy analysts Robert Socolow and Alexander Glaser argue: ‘If nuclear power is sufficiently unattractive in such a deployment scenario, nuclear power is not on the list of solutions to climate change’ (Socolow and Glaser 2009, 35). By this measure, if the opposition to Iran’s nuclear power efforts from a number of countries is any indication, it is unlikely that nuclear power can become an effective solution to climate change.

Two implicit but flawed assumptions underlie the nuclear industry’s oft-heard claims about the significance of nuclear energy in controlling climate change. The first is that climate change can be tackled without confronting and changing Western, especially American, patterns of energy consumption—the primary causes and continuing drivers for unsustainable increases in carbon emissions and global warming. It seems highly unlikely that climate change can be mitigated while maintaining the current consumption levels in developed countries. Efforts by various developing countries—especially by the elite in such countries—to match these consumption levels only intensify the problem.

The second is that, empirically, the adoption of nuclear power by itself does not seem to make sense as a strategy for lowering aggregate, society-wide carbon emissions. Let us consider the case of Japan, a strongly pro-nuclear-energy country. Jinzaburo Takagi, Japanese nuclear chemist and joint winner of the 1997 Right Livelihood Award, observed that, from 1965 to 1995, Japan's nuclear plant capacity went from zero to over 40,000 MW. During the same period, carbon dioxide emissions went up from about 400 million tonnes to about 1200 million tonnes. In other words, increased use of nuclear power did not really reduce Japan's emission levels (Byrne et al. 2000). In the case of France, there was a decrease in emissions during the phase of intensive nuclear reactor building but, since 1985, its per capita emission levels have been roughly constant (Glaser 2010). Reliance on nuclear power alone, therefore, is unlikely to get countries like Japan and France to reduce their emissions.

There are two reasons why increased use of nuclear power does not necessarily lower carbon emissions. First, nuclear energy is best suited to produce baseload electricity, which constitutes only a fraction of all sources of carbon emissions. Other sectors of the economy, such as transportation, where carbon dioxide and other greenhouse gases are emitted, cannot be operated using electricity from nuclear reactors, at least in the near future.

A second and more fundamental reason is that, because nuclear technology is an expensive source of energy, it can be economically viable only in a society that relies on increasing levels of energy use. Nuclear power tends to require and promote a supply-oriented energy policy, and an energy-intensive pattern of development, and thus, in fact, indirectly adds to the problem of global warming (Byrne et al. 2000). In contrast, aggressively pursuing measures like consumption reduction, energy efficiency and renewables, and trying to make them as effective as possible would lead to other changes in the way that we organize society and production, for example, a more decentralized and localized economy that would further undercut the rationale for nuclear power. As energy analysts Antony Froggatt and Mycle Schneider have argued, 'From a systemic point of view the nuclear and energy efficiency+renewable energy approaches clearly mutually exclude each other, not only in investment terms' (Froggatt and Schneider 2010).

This brings me to one of the questions I am often asked when I speak about this subject: what are the alternatives to nuclear power in India? I usually answer this by invoking a mathematical metaphor—pointing out that the question is unanswerable because it does not provide the boundary conditions needed to solve the problem. In other words, answering this question requires the specification of the constraints under which alternatives can be explored. The questions that come up include: should we use the energy source with the lowest direct cost? How does one assess the long-term value of the land and other natural resources that the generation of energy might need? What about displacement of people? How much pollution is socially permissible? What kinds of pollutants—particulates, carbon dioxide, or radioactive effluents—are acceptable? How much extra cost is allowed in order to avoid some of these pollutants? If one is serious about specifying alternatives, then, these questions and many more have first to be answered.

There are also larger concerns that have to be addressed when thinking about alternatives to nuclear power. By and large, those raising this question think about different sources of power as though they were pieces of a Lego set, in which one can easily replace one source for another. But, each source of energy comes with its own set of infrastructural requirements and demands, and produces potentially very different social and political outcomes. Think, for example, of the difference between installing two 1000-MW reactors in Koodankulam and installing the equivalent capacity of decentralized solar photovoltaic panels in rural communities around the country. For suitable choices of various physical parameters and operating histories, these two alternatives might produce the same number of kilowatt-hours of electricity, but their consequent social, economic, environmental and political effects would be vastly different. We will return to this issue of energy choices later.

Coming specifically to the question of climate change, there is so far no official position, let alone consensus, in India on what the long-term carbon emissions trajectory should be. Thus, using climate change as a justification for a nuclear expansion is disingenuous. To the extent that some commitments have been made at international forums to reduce the carbon intensity of India’s economy, it is likely that building nuclear reactors would be an expensive way to meet with those targets. If these nuclear reactors are to be hosted by poor, unwilling communities, then there is an additional ethical problem: those who have had little or no role in causing climate change, with emissions well below global averages, are being made to carry the burden of mitigating climate change, by having their lives and livelihoods altered, against their wishes, by these facilities, and by having to live with the risks associated with nuclear technologies.

Finally, as shown in chapter 8, nuclear energy cannot really lay claim to being environment-friendly; its fuel chain is polluting, albeit in a different way from that of fossil fuels. It also comes with the risk of catastrophic accidents and reduces the likelihood of achieving global and regional nuclear disarmament. Those who advocate nuclear energy because of concerns about global warming tend to ignore or belittle these concerns. Climate change may be a grave danger confronting us, but it should not blind us to other environmental and human risks.

FOUR PREDICTIONS

The physicist Niels Bohr is reported to have said, ‘Prediction is difficult, especially about the future.’ This is particularly true about nuclear power in India, because it is influenced by myriad factors. With that caveat in mind, I offer some inferences that flow from the logic of the arguments laid out in the book.

Nuclear Power in Energy Planning

Despite its failures in the past and the high costs associated with nuclear power, policymakers involved in energy planning have accorded an extremely prominent place to nuclear power. Why is this so and what does it mean for nuclear power in the future?

The answer to the first question starts from the observation that practically all official decision-making bodies which have set energy policies or developed energy plans have included members of the nuclear establishment. For example, one always finds DAE officials on various energy-related committees of the Planning Commission or the Central Electricity Authority or the Confederation of Indian Industry. The results of this presence can be seen in their outputs. As a member of the Working Group on Energy Policy (WGEP) observed some years after the group had completed its work, ‘The section on nuclear power in the WGEP Report reads like a public relations brochure of the Department of Atomic Energy and does not really examine any of the basic issues’ (T.L. Shankar 1985, 85). Moreover, a number of senior officials in important government ministries, external affairs in particular, have been seconded to the DAE during their careers, allowing them to internalize the DAE's self-image and version of history.

The Planning Commission was particularly important in the first couple of decades after Independence because it was 'the exclusive theatre where economic policy was formulated' (Khilnani 1997, 85). Since the 1960s, the Planning Commission has 'tended to accept the DAE's recommendations because (a) the latter body is said to be technically qualified to pass judgement; (b) there is a desire to avoid internal disputes amongst government offices' (Hart 1983, 35).[7] An early example of the Planning Commission essentially repeating arguments put out by the DAE was in the III Five-Year Plan, which expounds on the benefits of the three-phase programme without independent assessment (Bhatia 1979, 102).

This state of affairs has not changed in all these decades. The most recent official document on energy planning in India is the 2006 report by the Expert Committee on Integrated Energy Policy of the Planning Commission. The committee included Anil Kakodkar, Secretary, DAE, and concluded, inter alia, that 'Nuclear energy theoretically offers India the most potent means to long-term energy security … Continuing support to the three-stage development of India's nuclear potential is essential' (Planning Commission 2006, xxii).

Reports by such high-powered bodies do not analyse either the performance of the DAE or its projections for the future.[8] Instead, they invariably extol the importance of nuclear power in meeting India's electricity demand without looking at any other considerations, including economics. For example, the Central Electricity Authority's Expert Committee on Fuels for Power Generation, whose task it was to 'assess the relative economics of the various fuels' opined that 'nuclear energy has the potential of providing long-term energy security to the country and all research and development efforts must be pursued to realize this objective', but with the explicit admission that 'the costs of generation of nuclear projects have not been calculated' (CEA 2004, vi).

Such pronouncements bring to mind the admonition of Daniel Greenberg, former editor of the journal *Science*: 'Don't ask the barber whether you need a haircut' (Greenberg 1972, 58). Unless there is a change in the way decisions about energy policy are made, it is likely that government policy will continue to emphasize nuclear power as the answer to India's energy needs in the long term and the DAE will continue to receive large budget allocations.

The Breeder Programme

Will the breeder programme survive?

As argued earlier, there are good reasons to stop constructing breeder reactors and as such, there is no physical or technical reason that India should continue to pursue this problematic technology, even if the commitment to nuclear power persists. This is the case with France, which has continued to favour nuclear power—although the share of nuclear power will reduce as a result of policy changes following the Fukushima accidents—but has, for all practical purposes, given up on its plans for breeder reactors. However, there is a profound difference between France and India. There has been some official effort in France to evaluate the nuclear industry. For example, in the late 1990s, Prime Minister Lionel Jospin commissioned a report on the economic prospects of the nuclear electricity sector. Coming on the heels of the disastrous performance of the Superphénix reactor, the Charpin report found that reprocessing and the use of the so-called MOX fuel that contains plutonium are uneconomical and will remain so for the foreseeable future (Charpin, Dessus, and Pellat 2000). It is a different matter that the government decided to continue with reprocessing because of sunken costs and other considerations.

In India, on the other hand, there has never been any public questioning of the breeder programme by government officials. Indeed, at every opportunity possible, political leaders have praised this strategy. For example, when dedicating a new reprocessing line in Tarapur, Prime Minister Manmohan Singh described it as 'a milestone in India's three-stage nuclear programme' and pointed out that it was 'essential for subsequent thorium utilization' (ToI 2011). The DAE has tried to capitalize on this by portraying itself as a world leader in breeder technology. Given the global trend away from breeder reactors, that status is not very difficult to attain.

There is also the legacy of Homi Bhabha that cannot be easily done away with, after having spent decades putting him on a lofty pedestal. In the eyes of some, the DAE's raison d'être is the fulfilment of the Bhabha three-phase programme. The commitment to the three-phase programme, therefore, is never questioned. The differences within the DAE expressed publicly by various retired officials during the negotiations of the US–India deal related in a large part to the question of what the deal meant to the Bhabha dream. The critics argued that by importing LWRs, the government was abandoning breeder reactors and plans for the use of thorium. Those supporting the deal reiterated their commitment to the same programme, and portrayed the import of LWRs as just a temporary measure, meant to accelerate the nuclear programme and to provide even more plutonium for the construction of breeder reactors.

The DAE finds itself in the situation that political scientist William Walker (1999) has termed entrapment. Walker's case study of entrapment was also in the nuclear arena, and related to the British government finding that it could not extricate itself from the construction and operation of the Thermal Oxide Reprocessing Plant (THORP) even though there was a 'radical change in the market for its products, and in the perceived relative advantage of spent fuel storage and disposal over the reprocessing route' (Walker 2000, 839).[9] Likewise, even if some in the DAE or in the government should somehow find the courage and the sagacity to question the breeder programme, the institutional commitments to the three-phase programme are so great that it would be an uphill battle to get the DAE to abandon it. All in all, the breeder programme will survive for the foreseeable future, given that the sunken costs in the breeder programme are so high, the DAE's institutional commitment to breeder reactors is so great, and the ability of outsiders to hold the DAE accountable for potential failures so limited.

Newer Reactor Designs

What would the DAE do in the unlikely scenario that it is forced by the highest political circles to give up its breeder reactor pursuits?

That is clearly a politically remote possibility as long as the DAE continues to maintain its clout. But even if this were to happen, the DAE would offer a new type of nuclear reactor as a solution to India's energy problems. The DAE seems to have already decided on Plans B and C. In the last decade, the DAE, especially under Anil Kakodkar, began marketing the advanced heavy water reactor as an 'innovative' reactor with 'several new features' including the 'utilization of thorium on a large scale and inclusion of several passive safety features' (Sinha and Kakodkar 2006, 699). The design that has been developed since the 1990s involved the use of large quantities of plutonium as fuel. In 2009, Kakodkar announced that India had made an export version of this design called the AHWR-LEU, which would dispense with plutonium as input and, instead, use low enriched uranium (LEU) instead.[10] The 'market space' for which the DAE is aiming this reactor is the 'developing countries' which may have only a 'modest industrial infrastructure' (WNN 2009). This reactor might well become the next big technology that the DAE can use to reel off promises about using thorium for electricity generation, highlighting India's thorium resources and its long history of research on the subject. The appointment of R.K. Sinha, who has led the AHWR project for a while, as the chairman of the Atomic Energy Commission in 2012 suggests that this reactor design will continue to be actively promoted.

In the longer run, the DAE might try to go from merely promising electricity to promising other forms of energy. Its putative route into this larger arena is through the 'the Compact High Temperature Reactor (CHTR) to split hydrogen from water' (Subramanian 2009). Hydrogen, the article hopefully adds, 'would be the fuel of the future'. DAE's goal is to 'develop [an] alternate energy carrier to substitute fossil fuel based transport fuel' (Dulera and Sinha 2010, 65).

The bottom line is that, by one means or the other, the DAE has to be able to promise limitless abundant energy, even if it never manages to deliver on that promise. As described earlier, this is one of the two pillars of its political power.

Fissile Material Controls

What impact will progress in international nuclear arms control, including a possible treaty to end the production of fissile materials, have on the DAE's programmes?

Such a possibility threatens the other source of the DAE's political power, namely its ability to promise, though not deliver, strategic military security through the flawed notion of nuclear deterrence. The DAE is not interested in the actual quantity of fissile material available to it, but rather in the ability to produce large quantities should an appropriate rationalization arise. That is why, despite having accumulated the plutonium needed to make tens, if not hundreds, of nuclear weapons, the DAE has jealously guarded the ability to produce much more, by insisting on keeping a number of nuclear reactors outside of safeguards during the negotiations over the US–India nuclear deal.[11] AEC Chairman Anil Kakodkar said as much in his interview with Pallava Bagla in *Science*. When Bagla asked him: 'Is your strategic need for plutonium not met by CIRUS and Dhruva? Do you need additional capacity from civilian reactors?' Kakodkar replied explicitly in the affirmative with a significant correction: 'Yes, very clearly. Not from civilian reactors, but from power reactors' (Bagla 2006). Kakodkar's emphasis on the distinction between civilian reactors and power reactors implies that, for the DAE, a reactor's use for making nuclear weapons material is not to be precluded just because its main purpose may be to produce electricity. This tendency does not bode well for initiatives, such as the Fissile Material Cutoff Treaty, that seek to stop the production of material that can be used for making nuclear weapons.

To the extent it can, the DAE is likely to block progress on such initiatives as and when it becomes convinced that these treaties will be constraints on its own fissile production capabilities. Like nuclear weapons laboratories elsewhere, the DAE realizes that moves towards nuclear disarmament also render it less capable of claiming that it is contributing to 'national security', thereby undercutting its institutional clout.

Based on our argument of the sources of the DAE's political power, we see that it cannot change its dual focus on nuclear weapons and expensive electricity for the foreseeable future if it is to thrive. The DAE sees them as complementing each other in helping the organization continue its institutional pre-eminence in the current Indian government set-up.

MOVEMENTS FOR CHANGE

All these ‘predictions’ are contingent on the assumption that the nature of decision-making in the country does not change substantially. Such change is, of course, not impossible. Many countries have abandoned breeder programmes. Germany moved from being strongly committed to expanding nuclear power to phasing it out, a process that was only accelerated by the Fukushima accidents. South Africa gave up its nuclear weapons unilaterally. Can something of that sort happen in India?

The first thing to note is that just exposing the problems with nuclear power or with the DAE alone is insufficient to engender real change. Nuclear power means too much to too many powerful groups. For the elite, with their desire for great power status, nuclear power has been a symbol of modernity that could promise the means for mass production, consumption and destruction. Nuclear power is also tied to the nature of the Indian State, and has provided a means for it to legitimize itself. That said, neither the State nor the elite is homogeneous, and different groups have differing relationships with the nuclear dream. Therefore, it is necessary to lay out the costs and the consequences of nuclear ambitions. However, under the prevalent political conditions—where those most impacted by the nuclear enterprise are largely disempowered—it is unlikely that technical and economic arguments by themselves will suffice to change the course of energy (or weapons) policy.

To understand what may be required, one can look at the examples of countries that have dramatically shifted their nuclear policies. These cases show that major change will have to come from below, from large-scale social movements. In Germany, for example, the 1998 decision to phase out nuclear power resulted from a series of oppositional struggles at various nuclear sites going on since the 1970s and the growth of a large-scale environmental movement, from which the Green Party emerged (Glaser 2012). The strength of that movement is still visible, most recently through the large-scale protests that greeted Chancellor Angela Merkel’s slight changes to the nuclear phase-out law in the second half of 2010 (Graham 2010).

Yet another impact of the protests in Germany was the emergence of institutions and citizen groupings that explored alternatives to nuclear power, and cities and towns that committed themselves to reducing reliance on nuclear power. Freiburg, for example, has been described as a solar city

(Beatley 2007), and is a leader in energy-efficient housing. It also boasts of institutions such as Öko-Institute and the Fraunhofer Institute for Solar Energy Systems that have explored alternatives to nuclear power from policy and technical perspectives. The roots of this transformation go back to the protests launched against the 1975 decision to build a reactor in Wyhl, just 30 km from Freiburg. These efforts were strengthened when the radioactive plume from the 1986 Chernobyl spread over the city and much of Europe (Rogers 2010, 83–86).

India's version of these social currents is to be found in what have been termed people's movements. In recent decades, these movements have 'become an important part of India's social life and a driver of processes for democratising the public debate on policy issues' including issues related to energy and climate change (Bidwai 2009, 135). Such movements have been launched by local communities around the country who are increasingly unwilling to give up their lands, livelihoods and control over natural resources for nuclear power stations, or for other mega development projects, including automobile factories, large dams, and mines. Those suffering loss of land and access to natural resources are disproportionately the poor. Sociologist Amita Baviskar (1995) has argued:

> the bulk of development policies, justified in the 'national interest', actually diminish poor people's ability to control and gainfully use natural resources. Every 'national' project is presented as beneficial for the masses even though it requires some poor people to surrender their land or their livelihood. While the 'greater good of the nation' appears to be a laudable cause, it must appear suspicious to the rural poor who are consistently chosen, time and time again, to make all the sacrifices, while those more powerful reap the benefits. (32)

The demands on the lands, livelihoods and other resources are only going to intensify if the current pattern of development continues (Shrivastava and Kothari 2012). A landmark study published by the Centre for Science and Environment in 2009 examined the performance of the six most energy- and emissions-intensive sectors of Indian industry and projected how they would evolve if economic growth were to continue at 8 per cent for two decades. The study estimated that just these sectors would require 1 to 1.3 million hectares of land, and that freshwater consumption would increase more than threefold by 2030 (Bhushan 2010).

Over the last decade, it has become clear that the rural poor are fiercely resisting such 'development' projects. In the case of proposed nuclear projects, local inhabitants have not allowed the DAE to carry out surveys of soil composition, have refused to accept compensatory packages, and have engaged in various other acts to express their opposition. Most recently, this resistance has been dramatically highlighted by the struggle in the villages surrounding the Koodankulam reactor to stop its commissioning. These actions exemplify the observation of the civil liberties activist and intellectual, the late K. Balagopal (2009): 'The experience of this country is that governments do not stop doing something merely because it has been demonstrated to be bad. Or even contrary to constitutional directives and goals. They stop only if going along is made difficult to the point of near impossibility. No democratic dispensation should be thus, but Indian democracy is thus.'

These movements have raised fundamental questions about how energy policymaking has been carried out, namely, as a decision to be made by technical experts, economists and bureaucrats. Energy policy choices—whether the decision to expand nuclear power on a large scale, or to continue relying on coal, or to build numerous large hydroelectric dams—imply far more than just how electricity is generated. The lives and livelihoods of millions will be directly impacted by these decisions. Energy choices will also determine the form of development that India undergoes—the distribution of wealth and income, the kinds of jobs that are created, and so on. Therefore, it is important that decisions about energy policy be made by a genuinely democratic process.

This process would involve asking a lot of hard questions: what kind of development is desirable? Who benefits and who suffers from various development choices? What if we are running out of resources or if there are other environmental constraints? Seen this way, the first question to address becomes not which energy sources are chosen but how and through which processes those choices are made.

One common argument that is used to try and confine this debate to a small and narrow circle of 'experts' is the claim that deciding on energy choices requires exotic and specialized knowledge. It is precisely to counter such thinking that this book has emphasized that many of the nuclear establishment's claims can be checked using data in the public domain. Some only require fairly simple calculations, while others require involved work and data collection. The reason for illustrating this with so many examples is to foster the realization that even if the nuclear establishment tries to assert or otherwise give the impression that it alone possesses the esoteric expertise to make pronouncements on some issues, it can be challenged. Matters of public policy that affect large numbers of people can indeed be democratically debated with reasonable, if not full, cognizance of the issues involved.

In a post-Fukushima world facing catastrophic climate change, widespread inequity in access to energy, and the ever-present danger of nuclear war, decisions about nuclear power, or energy policy in general, are far too important to be left to official experts. It is vital that each of us, to the extent possible within our individual capacities, strives to recover decision-making on such important issues from institutions with vested interests. I hope this book makes a modest contribution to such a recovery.

Appendix 1

Nuclear Reactor Types

All existing nuclear reactors are based on the process of nuclear fission, by which the nucleus of a very heavy atom, such as uranium or plutonium, splits into two lighter nuclei. During this process, energy is released. Fission of a heavy nucleus can be spontaneous or induced by the absorption of a neutron. During fission, extra neutrons, typically two or three, are released. Under some circumstances, these neutrons could be absorbed by other heavy nuclei, in turn causing these nuclei to split, and so on, thus leading to a chain reaction.

The minimum amount of fissionable material that is needed to start and sustain a chain reaction is called the critical mass. When a reactor first maintains a chain reaction, it is said to have become critical or reached criticality. Nuclear reactors are designed not only to achieve a chain reaction, but to do this in a self-sustained fashion so that they can steadily produce energy. The region of the reactor where this self-sustaining chain reaction occurs is called the nuclear core, or simply the core.

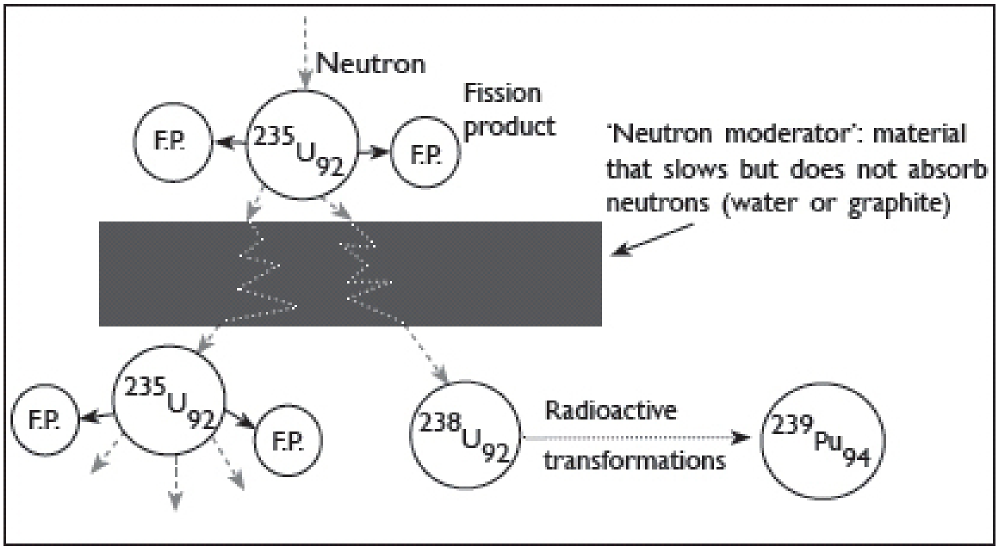
The probability of the released neutron being absorbed by another nucleus decreases with the energy or the speed of the neutron. In turn, the probability of the absorbing nucleus going on to fission depends on the energy of the neutron. In fissile nuclides, fission is possible with neutrons of any energy. The most important fissile nuclides are the uranium isotopes, uranium-235 and uranium-233, and the plutonium isotope, plutonium-239. Isotopes have the same number of protons and electrons, but differ in the number of neutrons. Of these, only uranium-235 is found in nature but in very low concentrations. Uranium, as found in nature, contains 0.7 per cent uranium-235 and 99.3 per cent uranium-238. The latter isotope of uranium

—as well as isotopes, such as plutonium-240 and thorium-232—can be fissioned by neutrons, but only if they have energies in excess of about a million electron volts (Knief 1992, 41).

When they are emitted during fission, neutrons are energetic. Because of the low probability of absorption of energetic neutrons, maintaining a chain reaction requires either a large concentration of fissile materials or that the neutrons be slowed down. Those reactors where the neutrons are not slowed down are called fast neutron reactors and those where the neutrons are slowed down are called thermal reactors.[12]

The slowing down is achieved by interposing materials made of light nuclei, typically water or graphite. These materials ‘moderate’ the neutrons. Once slowed down, it may be possible to sustain a chain reaction even with natural uranium, in which uranium-235 constitutes only 1 out of 140 uranium atoms but captures about half of the slow neutrons (von Hippel 2010, 4). The remaining atoms in natural uranium, virtually all non-fissile uranium-238, capture most of the other half of the slow neutrons and are thereby converted into plutonium-239. Such materials that can be converted into fissile materials by absorbing neutrons are called fertile materials.

APP.1.1: A FISSION CHAIN REACTION


Neutron
Fission product
F.P.
$^{235}U_{92}$
F.P.
'Neutron moderator': material that slows but does not absorb neutrons (water or graphite)
F.P.
$^{235}U_{92}$
F.P.
$^{238}U_{92}$
Radioactive transformations
$^{239}Pu_{94}$

Courtesy: von Hippel 2010, 6.

A typical fission produces about 200 million electron volts (MeV) of energy. Over 80 per cent of this is in the form of the kinetic energy of fission products. This energy, in turn, is transferred to ‘the coolant’, a material that is used to extract the heat produced in the core. If the coolant is liquid, it could either be allowed to boil and directly drive a turbine generator to produce electricity or it could be maintained under high pressure so that it remains liquid and transfers its heat to a secondary fluid that is allowed to boil and drive a turbine.

The most widespread nuclear reactor type today is the light water reactor (LWR), which uses water as moderator and coolant.[13] Due to neutron absorption in water, such reactors require fuel that has a slightly higher concentration of fissile material than natural uranium. Typically, uranium enriched to about 3 to 5 per cent in uranium-235, or low enriched uranium (LEU), is used as fuel. There are two categories of LWRs—pressurized water reactors (PWRs) and boiling water reactors (BWRs)—each of which comes in multiple varieties. Among the operating power reactors, as of July 2012, there were 272 PWRs and 84 BWRs (IAEA 2012). Other types of reactors operating across the world were 47 pressurized heavy water reactors (PHWRs), 15 gas-cooled, graphite-moderated reactors (GCRs), 15 light-water-cooled, graphite-moderated reactors (LWGRs), and 2 fast breeder reactors (FBRs).

The Indian nuclear programme is dominated by PHWRs. According to the DAE’s plans, the bulk of the reactors to be constructed over the next few decades will be FBRs. We therefore describe these two reactor types in slightly more detail.

PHWR

Heavy water reactors were pioneered by Canadian nuclear engineers. Though Canada had played a part in fission research during the Second World War and the Manhattan Project that developed the first atomic bombs, it did not embark on a weapons programme. One specific focus of Canada’s efforts during the war was the production of heavy water (HW). Thus, it decided to develop the so-called CANDU (for CANada Deuterium Uranium) reactor that used HW as both moderator and coolant.

The heart of a CANDU reactor is a horizontal cylindrical stainless-steel tank called the calandria.[14] The tank contains heavy water which is used to moderate the neutrons emitted during fission. The moderator is at a relatively low pressure and temperature. At both ends of the cylinder are two parallel plates, the so-called end shields, which are perforated with a number of holes (306 for a 220-MW reactor and 392 for a 540-MW reactor). Through each of these holes there runs a horizontal tube made of an alloy called zircalloy with a trace of niobium. Inside each of these tubes is another tube, the so-called pressure tube, with a slightly smaller diameter. This contains twelve fuel bundles, and each bundle contains nineteen fuel elements. Each fuel bundle is about half a metre in length and contains about 13 kg of uranium. The uranium is not enriched and contains 0.7 per cent uranium-235.

The coolant heavy water, which carries away the heat produced during fission, flows through the pressure tubes. This heavy water has to be under high pressure; because it is usually quite hot (around 250° to 300° Celsius), at normal pressures it would become steam.[15] After the heavy water passes over the fuel bundles and becomes hot, it comes out of the calandria and eventually into steam generators, where it transfers heat to ordinary water. This water turns into steam and drives turbines to produce electricity.

The rate of fission reactions in the reactor is controlled by rods made of neutron-absorbing materials such as cobalt. In the more recent 540-MWe design, this is done using water, which also absorbs neutrons (Bajaj and Gore 2006, 706). By adjusting the length of the rod that is inside the active core, the number of neutrons absorbed can be changed and, thereby, the power level of the reactor.

PHWRs are designed to be refuelled continuously while the reactor is running and producing power. This is done through the use of refuelling machines, which replace fuel bundles in adjoining fuel channels carrying fuel bundles.[16] As a new fuel bundle is loaded at one end, an old fuel bundle is pulled out at the other end. The used fuel bundle is sent to a cooling pond holding water for the rate of heat and radioactivity release to decrease.

One of the claimed benefits of the CANDU design is that it does not require a large pressure vessel as used by light water reactors (Bajaj and

Gore 2006). A large pressure vessel is difficult to manufacture. But this advantage is achieved through the use of many pressure tubes.[17] Though the pressure tubes are built to withstand high pressures, it is possible that they could break due to various reasons. Then, the coolant pressure would reduce to atmospheric pressure or thereabouts and the heavy water would immediately be converted to (‘flash into’) steam.

FAST BREEDER REACTORS

In fast neutron reactors, neutrons are not slowed down and the chain reaction is sustained because the reactor’s core contains a high concentration of fissile material, usually plutonium-239. Surrounding this core on all sides is a ‘blanket’ made of uranium or thorium containing fertile isotopes like uranium-238 or thorium-232 respectively. Typically, a large number of neutrons produced in the core as a result of fission reactions will escape from the core. These neutrons are captured in the blankets, and the fertile isotopes therein get converted into fissile plutonium-239 and uranium-233. Thus, the reactor, if designed appropriately, could produce (breed) more fissile material than they consume, and are hence called fast breeder reactors.[18]

The use of fast neutrons has advantages and disadvantage. The advantage is that if a plutonium-239 nucleus absorbs fast neutrons, it releases 2.7 neutrons on average (Nero 1979). The corresponding number for uranium-233 is 2.6. Even if one of these neutrons goes on to continue the chain reaction, and another to convert a fertile nucleus into a fissile one, thereby replacing the fissile material that is consumed, in the majority of fission reactions, there will be an additional neutron that can produce another fissile nucleus. That is how such reactors breed additional fissile material.

The disadvantage is that the probability of a fast neutron initiating fission in the first place is low as compared to thermal neutrons. Several hundred times as many fast neutrons as thermal neutrons would be needed to cause each fission. This means that a much higher neutron density must be created. Therefore, even to maintain a chain reaction, the core of the reactor has to have a relatively high concentration of fissile material. In addition, the neutrons that come out of the fission reaction must avoid collisions that would slow them down. This means that there should be no moderator, a minimum of other structural material, and as little coolant as would suffice to carry away the intense output of heat (Patterson 1976, 50).

Because of the lack of a moderator, fast breeder reactor cores are more compact. Therefore, the energy that they produce is concentrated in a much smaller volume. This necessitates the use of a coolant that can efficiently carry away this heat, usually a liquid metal. Most breeder reactors use molten sodium.

The use of sodium, again, has advantages and disadvantages. In addition to its heat transfer properties, the important advantage with sodium is that it remains a liquid up to a high temperature. This means that it does not have to be kept under pressure to avoid boiling under normal circumstances. It does mean, however, that throughout its sojourn in the reactor and outside, its temperature should never fall below its melting point, lest it solidify.

The most important problem with sodium should be familiar from school chemistry text books: sodium reacts violently with water. At reactor-operating temperatures, it burns if exposed to air (Nero 1979, 205). Accordingly, it must be covered by an inert gas such as argon. This, in turn, could form unwanted bubbles in the sodium as it flows. The other problem with sodium is that it is opaque. Thus, any kind of inspection of the internal parts of the reactor needs complicated equipment.

Finally, when sodium absorbs a neutron it becomes an intensely radioactive isotope, sodium-24, which emits gamma rays. This means that all the sodium that could be exposed to neutrons—the so-called primary circuit—must be confined within the concrete shielding of the core. This radioactive primary sodium, in turn, gives away all the heat to a second sodium circuit in a device called a heat exchanger, which has to be inside the concrete shielding but is itself shielded from neutrons so that the secondary-cycle sodium does not become radioactive. The secondary sodium carries away the heat to another heat exchanger in which steam is generated. In these steam generators, molten sodium and water are separated only by thin walls and have proved to be one of the most troublesome features of breeder reactors.

Appendix 2

The US–India Nuclear Deal

On 18 July 2005, US President George W. Bush and Prime Minister Manmohan Singh issued a joint statement laying the grounds for the resumption of US and international nuclear aid to India.[1] The statement required the United States to amend both its own laws and policies on nuclear technology transfer, and to work for changes in international controls on the supply of nuclear fuel and technology so as to allow 'full civil nuclear energy cooperation and trade with India'. The United States also promised to consult with partners about India's inclusion in the ITER (International Thermonuclear Experimental Reactor) project to study nuclear fusion, and in the Generation IV collaboration to develop new nuclear reactor designs.

In exchange, the Indian government agreed to identify and separate 'civilian and military nuclear facilities and programs in a phased manner'; 'place voluntarily its civilian nuclear facilities under IAEA safeguards'; continue the country's 'unilateral moratorium on nuclear [weapons] testing'; 'work with the United States for the conclusion of a multilateral Fissile Material Cut-Off Treaty'; refrain 'from transfer of enrichment and reprocessing technologies to states that do not have them and [support] international efforts to limit their spread'; and ensure 'that the necessary steps have been taken to secure nuclear materials and technology through comprehensive export control legislation and through harmonization and adherence to Missile Technology Control Regime (MTCR) and Nuclear Suppliers Group (NSG) guidelines'.

Both countries were going against their historical policies: the United States with regard to its stance on nuclear non-proliferation, and India with regard to its long-standing opposition to having international safeguards at domestically constructed nuclear facilities. There was, therefore, considerable surprise at this shift in position, especially the US position. As time went on, this built up into resentment at the unilateral challenge posed by the United States to collective norms, concern about the threat to the already fragile non-proliferation regime, and widespread opposition. The various twists and turns of the sequence of events that led from the 2005 joint statement to the decision in September 2008 by the Nuclear Suppliers Group to waive India from its usual strictures have been described in great detail in newspapers and magazines during that period. Only a short summary is offered here.

In March 2006, India came out with a separation plan and offered to subject eight Indian power reactors to IAEA safeguards, in a phased manner. This was in addition to the six reactors that were already subject to safeguards because they had been purchased from abroad.[2] The reactors to be put under safeguards are Kakrapar I and II, Narora I and II, RAPS III and IV, and RAPS V and VI.[3] However, a significant proportion of India's nuclear complex will remain outside IAEA safeguards and could have a 'strategic' function. This unsafeguarded nuclear complex includes the TAPS III and IV, MAPS I and II, and Kaiga I to IV.[4] Moreover, India will not accept safeguards on the prototype fast breeder reactor (PFBR) and the fast breeder test reactor. Facilities associated with the nuclear submarine propulsion programme would not be offered for safeguards. Reprocessing and enrichment facilities are also to remain outside safeguards.

The decision to keep the fast breeder reactors out of safeguards was contentious. The reason was that the PFBR could be the source of a significant quantity of weapon-grade plutonium.[5] In February 2006, AEC Chairman Anil Kakodkar stated in an interview to the *Indian Express*, 'Both from the point of view of maintaining long-term energy security and for maintaining the "minimum credible deterrent", the Fast Breeder Programme just cannot be put on the civilian list' (Bagla 2006). At the time of the interview, Indian and US interlocutors were in the thick of negotiations over which set of facilities to be put under safeguards would be acceptable to both countries. Most reports indicated that the US team was interested in ensuring that the breeder would be under safeguards (see, for example, Varadarajan 2006), and there were some indications that the Indian side was willing to concede the point. Kakodkar's interview, therefore, constituted an unprecedented statement by a civil servant in government service to intervene in a matter of foreign policy in such a public fashion.[6] That he suffered no disciplinary action indicates the extent of political power wielded by the DAE.[7]

The agreement between the two countries over the separation plan was followed by the United States Congress passing the Henry J. Hyde US–India Peaceful Atomic Energy Act in December 2006. The Act went through the US Congress after a conference committee of its two chambers reconciled the separate bills that had passed through the two Houses of the US Congress. To get this result, Secretary of State Condoleezza Rice had to intervene personally on behalf of the Bush administration by writing a letter to Congress members urging them to accommodate India's concerns about the conditions sought to be imposed on it (Bidwai 2006). This was followed by the United States and India negotiating what was called the 123 Agreement, thus named because it amended Section 123 of the US Atomic Energy Act of 1954. This section regulates US cooperation with other nations in nuclear matters and prohibits trading with states that have not signed the Non-Proliferation Treaty (NPT). Negotiations between US and Indian interlocutors were contentious and took place over many months at meetings held on four continents. The two sides reached an agreement in August 2007, though there were substantial differences in the way the agreement was presented by the two governments to the public and lawmakers within the United States and India respectively.

The action then shifted back to India, because the next step in the process involved India's negotiating a safeguards agreement with the IAEA. However, at this point, the Left parties, whose support was essential for the ruling United Progressive Alliance coalition, threatened to withdraw that support if the government went ahead with the deal. The main opposition party, the BJP, was also opposed to the deal. Fearing that its government might be brought down, the Congress did not go on to the IAEA negotiations. The stand-off continued for some months. Prime Minister Singh maintained that he was keen on finalizing the deal, but wanted to do so after getting 'the broadest possible consensus in the country' (Ghoshroy

2008). For a while, it seemed as though the deal was essentially dead because it was deemed impossible to meet the various deadlines needed for the Bush administration to approve it while it was still in office. In October 2007, for example, the prime minister said, ‘If the deal does not come through, it will be disappointing. But in life, one has to take disappointments. The deal is not the end of life’ (Sahgal and Bhattacharjya 2007). Finally, a rapid series of events led to the Left parties withdrawing support to the UPA government in July 2008, the Samajwadi Party switching over to support the UPA on the deal, and the ruling coalition seeking and winning a vote of confidence in Parliament in a way that ‘exposed the seamy side of India’s … democracy’ (Bidwai 2008).

The domestic obstacles to the deal being overcome in the United States and India, the proponents of the deal turned to the other constituents of the Nuclear Suppliers Group (NSG). Countries that traditionally supported a strong non-proliferation regime, especially New Zealand, Ireland, the Netherlands, Switzerland and Austria, insisted that various conditions be applied to India’s nuclear programme before the NSG allowed the resumption of nuclear trade. Others joined them. But these states were stifled by the United States, which engaged in what Jayantha Dhanapala, former UN Under-Secretary-General for Disarmament Affairs, described as a campaign of ‘brutal and unconscionable pressure’(IPPNW-Europe 2008). Ultimately, the ‘participating governments’ of the NSG agreed to transfer various nuclear ‘related technology to India for peaceful purposes and for use in IAEA safeguarded facilities’ (NSG 2008).

The finale of this process in the United States was to get the 123 Agreement approved by the US Congress. Once again, there were many questions asked by various Congressmen on the nature of India’s commitments. But the Bush administration rammed it through as time wound down in its fall 2008 session under cover of the financial crisis (Lichterman and Ramana 2010). The Senate vote was overshadowed by the debate on massive bank bailouts that were pending the same day.

NUCLEAR DREAMS AND SHORTFALLS

On the face of it, the DAE had performed a major volte-face by agreeing to allow the IAEA to safeguard some of their ‘indigenously constructed’ nuclear reactors. That an institution—which claimed to be, in the words of R. Chidambaram (1999, 6), former AEC chairman, the ‘torch bearers of self-reliance’ and which had achieved ‘immunity against technology denial’—had given up a long-held position in order to be able to import technology from elsewhere, requires some explanation.

The DAE’s interest in being allowed to import nuclear technology was not new. As discussed in chapter 1, such international support was the key to India’s developing its nuclear infrastructure and capabilities. The decision by various nuclear supplier countries not to engage in nuclear trade with India after the 1974 nuclear weapon test had significantly set back its nuclear power programme. The DAE has subsequently expressed its keenness to import nuclear equipment, but not if it were to interfere in any way with its second source of political support: the ability to make nuclear weapon material. Though countries like Russia and, to some extent, France have been sympathetic, and Russia had even agreed to construct the Koodankulam reactors well before the NSG waiver, the real country that had to be swayed was the United States, and Indian diplomats never lost an opportunity to remind US representatives of that.

That said, the US–India deal represented one of those few moments in history when the fractures in the DAE’s external visage were quite visible. Retired DAE officials bickered publicly in the media, finding fault with each other’s position on the importance of the deal. The position of the critics of the deal within the DAE was characterized by former AEC chairman M.R. Srinivasan (2006), who supported the nuclear deal, as follows:

> One set of these critics feel that the earlier situation of total independence of the programme must be preserved at all costs into the indefinite future. They are prepared for a slow growth of nuclear power for the next two or three decades and an acceleration later, based largely on fast breeder reactors and thorium based systems. In this view, the freedom of the country with respect to the size and diversity of the nuclear deterrent would be maintained fully. It is not adequately appreciated that a small nuclear power programme continuing for another two or three decades may well result in a loss of interest and an eventual abandonment of the programme.

The concern over the loss of interest on the part of the government was at the heart of the DAE’s interest in the nuclear deal. A second motivation was a shortage of uranium. Since NSG rules prohibited the selling of uranium to India, the DAE could not import uranium. Only in the case of those reactors under international safeguards had India managed to import uranium. The remaining PHWRs had to be fuelled with domestic uranium produced at the mines and mills of the Jaduguda area. In 2008, the PHWRs had a combined capacity of 3800 MW. Assuming that they operated at a capacity factor of 80 per cent, they required about 545 tonnes of uranium per year as fuel. Apart from these reactors, domestic uranium was also used to produce plutonium for nuclear weapons at the CIRUS (since shut down [Laxman 2011]) and Dhruva reactors, and to produce enriched uranium at the Rattehalli facility. Together, all these would have required about 600 tonnes of uranium.

As of 2008, the five operating mines in the Singhbhum region were producing, roughly, an estimated 270 tonnes of uranium every year, assuming an average ore grade of 0.04 per cent. This was clearly much lower than the demand for uranium and the only way the DAE was able to operate its reactor was to draw on its uranium stockpile saved from earlier years, when there was more uranium being mined and the demand was lower. As an official 'close to the prime minister' told the British Broadcasting Corporation, 'The truth is we were desperate. We have nuclear fuel to last only till the end of 2006. If this agreement had not come through we might have as well closed down our nuclear reactors and by extension our nuclear program' (Srivastava 2005). Though there was a bit of hyperbole in that statement, it explained why many of NPCIL's reactors had to be operated at lower capacity factors by 2007 (Subramaniam 2007; PTI 2007a).

To emphasize the obvious, the shortage was not because there was insufficient uranium in the country, just that not enough uranium was being mined out of the ground. The failure was due to poor planning on the part of the DAE. The department could either have started mining operations earlier or slowed down the rate of reactor construction. The problem was not sudden either. In 2005, the former head of the Atomic Energy Regulatory Board had noted that 'uranium shortage' has been 'a major problem for the officials of NPCIL and the Nuclear Fuel Complex (NFC) for some time' (Gopalakrishnan 2005, 2936).

There was yet another reason to import uranium. By fuelling those reactors which it chose to put under IAEA safeguards with uranium purchased from international sources, the DAE could free domestic uranium for potential use in the nuclear weapons programme. This option has been suggested by, among others, K. Subrahmanyam, former head of the National Security Advisory Board, who argued that, ‘Given India’s uranium ore crunch and the need to build up our … nuclear deterrent arsenal as fast as possible, it is to India’s advantage to categorize as many power reactors as possible as civilian ones to be refuelled by imported uranium and conserve our native uranium fuel for weapons grade plutonium production’ (Subrahmanyam 2005). As was emphasized time and again by Prime Minister Manmohan Singh and various other government officials, such production of fissile materials for nuclear weapons was not constrained by the deal, and was the reason for the DAE’s insistence on keeping several of its reactors outside of safeguards.

For these reasons, and others, many in the DAE were anxious that the deal go through. To achieve this, they resorted to various stratagems. First, they played on themes of discrimination and colonialism. The term apartheid was invoked on occasion. AEC Chairman Kakodkar went on to declare: ‘If we don’t do it now, history will not forgive us’ (IANS 2008). Then they played on the Bush administration’s rationalization that the nuclear deal would help reduce India’s demand on global fossil fuel resources.[8] Speaking at a plenary session at a conference organized by the US Department of Energy, Ravi Grover, director of the Strategic Planning Group at BARC, projected the following figures: ‘The present hydrocarbon usage in India is about 2.5 per cent of the worldwide usage and this would grow to about 10 per cent by the middle of the century’ (Grover 2007).[9] And, finally, most important of all was the trope with which we started the book—the argument that, if the nuclear deal did not go through, then India would not be able to meet its energy needs. Given the many times we have seen the extent of the DAE’s fallibility when it comes to future projections, there is little reason to point out explicitly that this large-scale import requirement is baseless.

Even if this large shortfall does arise, nuclear power will not be able to grow rapidly enough to meet with it. As of July 2012, i.e., seven years since the July 2005 agreement, not even one imported reactor’s construction has started—an indication of how the DAE’s nuclear dreams are not magically going to suddenly start materializing even in the future.

To understand the reasons for the US switch in policies, and the relevance of this agreement, one has to go back to the earlier history of efforts for over fifty years to incorporate India into United States strategy in Asia (Mian and Ramana 2006). For decades, the United States saw India as the only regional power that could compete with China to dominate southern and South East Asia. But during the fifties and sixties, Prime Minister Jawaharlal Nehru rebuffed US efforts to use economic and military aid to induce India to play this role (McMahon 1994). American efforts 'to situate South Asia within its global strategy of anti-Soviet and anti-Communist containment' were also not welcome in India because they 'went directly against Indian efforts to insulate South Asia from the superpowers as part of its regional strategy and as a general principle of promoting disengagement from bloc politics everywhere' (Vanaik 1990, 237).

American hostility towards communist China led to various ideas about nuclear cooperation, including considering the possibility of 'providing nuclear weapons under U.S. custody' to India, preparing Indian forces to use them, and helping India with 'peaceful nuclear explosions', which would involve the use of US nuclear devices under US control being exploded in India (Perkovich 1999, 90–92). These plans were dropped amid growing fears of the consequences of proliferation for US military and diplomatic power and the United States turned, instead, to preventing the further spread of nuclear weapons. The new focus was crystallized over the late 1960s and the 1970s, with the Treaty on Non-Proliferation of Nuclear Weapons coming into force and the formation of nuclear export control regimes following the 1974 nuclear test. And from then on, the United States began to be seen as opposing India's nuclear ambitions, for energy or for weapons (Chellaney 1993).

Over the 1990s, as India went through a process of economic restructuring and increasing imports of foreign, including US, products, US perceptions of India started shifting. In 1995, the United States and India signed the 'Agreed Minutes on Defense Relations', the first of its kind (Karat 2007, 10). But even as the United States and India came closer in their economic and military relations, nuclear trade between the two was still curtailed. Also curtailed were space technology and military technology that could have non-military use as well, what is often termed dual-use technology. As M.R. Srinivasan wrote in 2003, ‘Everyone in India associates the Trinity with Brahma, Vishnu and Maheshwara. In the Indo–US diplomatic dialogue, however, trinity issues mean cooperation in civilian nuclear power, cooperation in civilian space research and export of dual-use technology’ (M.R. Srinivasan 2003). The weightage attached by Indian diplomats to these demands reflects the political power of the institutions—the nuclear, space and defence establishments—that desired the import of such goods, rather than something inherently problematic with export controls on these technologies.

After the 1998 nuclear tests, there had been an important series of diplomatic dialogues between Minister of External Affairs Jaswant Singh and US Deputy Secretary of State Strobe Talbott (Talbott 2007). The trinity issues figured constantly in these dialogues and Jaswant Singh and other Indian negotiators had tried hard to get the United States to allow nuclear trade. But, try as Jaswant Singh might, the United States under President Bill Clinton insisted that the precondition to any such opening of nuclear trade was the cessation of fissile material production for weapons and signing the Comprehensive Test Ban Treaty. The DAE had insisted on keeping open the option of conducting nuclear weapon tests and continued to manufacture plutonium and highly enriched uranium. The result was a stalemate.

The situation changed drastically after the US elections in 2000. The Bush administration that came to power cared little for arms control, refusing to push for ratification of the Comprehensive Test Ban Treaty, and not pursuing the Fissile Material Cut-off Treaty. But more important for India was the administration’s emphasis on old-fashioned military power politics. In an article published in the influential journal *Foreign Affairs*, Condoleezza Rice, the main foreign policy adviser to the future President George W. Bush in his presidential campaign, argued that the United States ‘should pay closer attention to India’s role in the regional balance … India is an element in China’s calculation, and it should be in America’s, too. India is not a great power yet, but it has the potential to emerge as one’ (Rice 2000, 56).[10]

Translating the idea of closer relations with India into drastic change in US policy had to wait for the second presidential term of George Bush when Rice became the Secretary of State.[11] Rather than earlier ideas that revolved around incremental easing of nuclear rules, Rice's idea was to pursue a 'big bang' approach aimed at bringing India firmly into the US camp (Kessler 2006). The details were left to a group of Rice's aides, in particular Philip Zelikow and Ashley Tellis, an adviser to Ambassador Robert Blackwill. All of them prepared the ground for a resumption of nuclear trade with India in different ways. Tellis, for example, wrote in one of his reports that the desire of Indian leaders to establish the country as a great one 'can be satisfied only by more liberal access to a variety of civilian technologies, such as nuclear energy, satellite components, and advanced industrial equipment' (Tellis 2005b, 7).

Recruiting India may help reduce the immediate costs to the United States of exercising its military, political and economic power to limit the growth of China as a possible rival. More generally, the United States sees Asia as central to global politics after the demise of the Soviet Union, and it needs strong regional clients there. 'The burgeoning U.S.–India relationship,' argues political scientist Achin Vanaik, 'must be situated geo-politically in American ambitions for Asia as part of its even wider project of constructing a Eurasian (and therefore global) dominance' (Vanaik 2008).[12]

This goal, it seems, is to be pursued regardless of how it will spur the spiral of distrust, political tension, and dangerous, costly, wasteful military preparedness between the United States and China, between China and India, and between India and Pakistan (Mian and Ramana 2006). And Indian policymakers have not been particularly resistant to helping the US advance its geopolitical objectives. An example is the Indian government's surprising vote for a US-led resolution against Iran at the September 2005 IAEA Board meeting, something key US lawmakers and officials had made clear was tied to the nuclear deal (Boese 2005). Till then, India had supported Iran's right to develop its nuclear programme in any way it saw fit. Its sudden switch can only be interpreted within the context of the deal and US pressure to join it against Iran. Indeed, Stephen Rademaker, former Assistant Secretary of State for International Security and Nonproliferation at the US Department of State, acknowledged that these ‘votes were coerced’ during a talk on ‘Iran, North Korea and the future of the NPT’ at the Institute for Defence Studies and Analyses in February 2007 (Varadarajan 2007).

At the domestic level, the Manmohan Singh government’s willingness to risk its own survival is an indication of the importance he and his advisers placed on the deal. As physicist Suvrat Raju argues, a believable reason for this was given by Ashley Tellis, who related the deal to ‘the president’s and the prime minister’s efforts to build a new sense of trust’ and it ‘implicates issues of credibility, issues of commitment, and finally issues of confidence for the future of the relationship’ (Haniffa 2007b). The same term, credibility, is also offered by Ronen Sen, India’s ambassador to the United States (Haniffa 2007a). The importance of this characteristic to the United States is that ‘Credible governments are those that do not allow *domestic political compulsions* to prevent them from adhering to American interests’ (Raju 2009) (emphasis in original).

THE MARKET AS MOTIVATION

Along with the geopolitical motivations, commercial interests offered an additional reason for the radical shift in US policy. In the United States, corporate interests led by the nuclear industry and arms makers were strong supporters of the deal. No sooner had Prime Minister Singh and President Bush released their joint statement than an unidentified spokesperson, when asked about whether the agreement should go forward, was quoted in one of the standard nuclear industry trade magazines as saying: ‘For the U.S., this may be clear since both Westinghouse [Electric Co.] and General Electric (GE) see potential sales in India supported by U.S.–Indian cooperation’ (Horner and Hibbs 2005). Even Thorium Power Ltd, a small US company that had explored the use of thorium in nuclear reactors—one of the areas in which the DAE prides itself on its great expertise—was interested.[13]

But nuclear trade was not all. US businesses were also greatly interested in selling various other goods and services to India’s newly affluent classes. Consumption by this section of society was projected to grow significantly in the next few decades (McKinsey 2007). That such sales would not be accessible to the majority of the people, and would foster a development model that would accentuate wealth disparities, was of no interest to them (Lichterman and Ramana 2008). The market was large enough for them to be keenly interested. As Ron Somers, president of US–India Business Council (USIBC), declared: ‘The bounty is enormous’ (Prashad 2007).[14]

At the same meeting that launched the nuclear deal in July 2005, President Bush and Prime Minister Singh also started the US–India CEO Forum in order to enhance bilateral trade and investment. Comprising ten CEOs each, from both countries, the CEO Forum put out a report titled ‘U.S.–India Strategic Economic Partnership’ that is perhaps the clearest and most concrete expression of what US business interests expected (T. Jayaraman 2006). Among the priorities that the CEO Forum insisted on were greater freedom to invest in services sectors, US investment into Indian infrastructure, and India setting up a dispute settlement mechanism which would have the power and jurisdiction to resolve commercial and contractual disputes quickly (US India CEO Forum 2006). Many saw these as inimical to the interests of the vast majority of Indians, but that was not the view of those setting the policies, many of whom saw this as a continuation or culmination of the economic liberalization efforts initiated in the early 1990s. The head of the Planning Commission, Montek Singh Ahluwalia, announced that a separate committee would be set up to consider every one of the recommendations. As T. Jayaraman of the Tata Institute of Social Studies, Mumbai, pointed out (2006), ‘The alacrity of this response, not accorded to even the main points of the Common Minimum Programme after the UPA government took office, is certainly striking.’

Commercial interests also helped smoothen opposition to the deal from members of the US Congress and others concerned with non-proliferation. US–India Business Council hired Patton Boggs, reportedly one of the most expensive lobbying firms in Washington, for an undisclosed sum, to push the deal (Ghoshroy 2006). In 2007, it also engaged Stonebridge International, another Washington lobbying heavyweight. USIBC also launched an advertising campaign to ‘raise public awareness about the benefits stemming from India’s civil nuclear opening: emphasizing … job creation and business opportunity’ (PRNewswire-USNewswire 2008). ‘The challenge is to make certain that nuclear power is generated safely. India’s nuclear program will be much safer with U.S. company involvement. Our elected officials need to hear this,' Ron Somers said.

For its part, the Indian government hired lobbying groups and reached out to an emerging force in US politics: the diasporic community (Kamdar 2007). Over the decades, Indians settled in the United States had organized themselves into political groups. Forming one of the most affluent ethnic groups in the United States, they have contributed millions of dollars to election campaigns. As a result, it was noted in 2002, the US 'Congress has taken notice. The Congressional India Caucus, founded in 1993, now has more than 120 members, nearly double that of the Congressional Study Group on Germany' (Lindsay 2002). These contributions were to increase even more in later years (Kurien 2007). These groups saw the nuclear deal as a kind of 'coming-of-age' moment, and a test of their ability to influence the US Congress. There were even reports of individuals quitting their jobs to do full-time lobbying. These efforts resulted in their becoming, in the words of Robert Einhorn, a US State Department official, 'an effective lobbying force' (Mufson 2006).

Among the lobbying groups engaged by the Indian government was Barbour, Griffith & Rogers. The firm is described as Washington's top-rated Republican lobbying firm and, during the crucial years for the deal from 2004 to 2008, was headed by Robert Blackwill after his term as ambassador to India (AKI 2006).[15] To balance politically, as it were, the government also engaged the services of Venable, a firm that used former Democrat senator Birch Bayh of Indiana as its point man for the nuclear deal. The idea, as Bayh told *Time* magazine, was to 'begin an educational process' (Waller 2006). The Confederation of Indian Industry is reported to have spent more than $1 million on flying US members of Congress, their staff and spouses to India (Stockman 2006).

An important part of this market was, of course, that involving nuclear reactors. The Manmohan Singh government appealed to their interests by providing a 'letter of intent' to the United States that stated its intentions to purchase reactors with at least 10,000 MW of new power generation capacity from US vendors and 'at least two sites to U.S. firms' (Varadarajan 2008). The most likely sites are Mithi Virdi in Gujarat and Kovvada in Andhra Pradesh. For their efforts in securing the NSG waiver, France and

Russia have also been rewarded with a site each: Jaitapur in Maharashtra for the former, and Haripur in West Bengal or some alternate site for Russia.

In addition to promising sites, the government also went ahead and subsidized these vendors by passing a nuclear liability bill that limited the amount these companies would have to pay as compensation for damages in the event of an accident. The liability cap of Rs 1500 crore was a small fraction of the capital cost of a modern nuclear reactor and an even tinier fraction of the monetary cost of dealing with a potential accident.[16] Thus, the bill not only socializes the risk of nuclear power (while vendors pocket the profits), but it will not even provide any incentives to companies to spend money to improve reactor safety (Raju and Ramana 2010a; Raju and Ramana 2010b; Ramana and Raju 2010b).

Partly in response to foreign, especially US, pressure, the government used executive fiat to weaken even this modest amount of liability held by the vendor. In November 2011, it notified two important ‘rules’ for the implementation of the law. First, it declared the ‘right of recourse’ mentioned above would be applicable only for the ‘duration of the initial license’ issued to the plant; this is usually only five years. Second, it stated that the operator would have the right to recoup the compensation it had paid to the victims but not the cost of the damage to the reactor itself.

In March 2012, the Supreme Court—after three preliminary but detailed hearings—admitted a public interest litigation case that questioned the constitutional validity of the liability law (Mahapatra 2012). At the time of this writing, the government had not responded. The two issues at stake here are whether the rules, as notified, are consistent with the original law, and whether the original law itself violates the fundamental right to life of the victims granted by the Indian constitution.

One argument that was invoked in support of the bill was that it was necessary to foster the growth of nuclear power. Else, the proponents of the bills argued, nuclear vendors would refuse to supply reactors and other pieces of technology. The argument echoed the argument used to strike the ‘sweetheart deal’ with Enron in the nineties (Ramana and Raju 2010a). Just as the Enron deal remained a one-off project and did not lead to a large-scale growth of similar plants, imports of nuclear reactors on terms favourable to vendors are unlikely to be a recipe for large-scale expansion of nuclear power.

Appendix 3

The Environmental Impact Assessment Process

In principle, the environmental impacts of nuclear power projects are regulated by the ministry of environment and forests (MoEF) through the environmental impact assessment process. This procedure started in 1994 when the government came out with the Environmental Impact Assessment (EIA) Notification. This was subsequently replaced with a revised one in 2006. These notifications put in place a formal process through which the potential adverse impacts of various developmental projects can be evaluated. At the end of the process, projects would be granted or denied a clearance from the MoEF.

The process for environmental clearance outlined in the EIA Notification 2006 starts with the MoEF receiving a detailed application on the basis of which the project is classified into a Central- or state-level project. The application also helps set the terms of reference for the EIA study. The project proponent then commissions an EIA study that is submitted to the MoEF, which, after being whetted by the ministry, is released to the public for their inputs. This is followed by a public hearing at a location (or locations) near the proposed project site during which members of the public can offer comments on the EIA and, more generally, on the project, either by speaking at the hearing or through written submissions. Taking the concerns of the public into account, an Expert Appraisal Committee (EAC) examines the EIA and either rejects, or more typically, grants environmental clearance, sometimes stipulating conditions to be followed by the proponent.[1]

The EIA Notification of 1994 listed ‘nuclear power and related projects, such as, heavy water plants, nuclear fuel complex, rare earths’, while the

EIA Notification of 2006 lists ‘nuclear power projects and processing of nuclear fuel’ as requiring environmental clearances. However, not all facilities involved in processing nuclear fuel are subject to this procedure. For example, the nuclear reprocessing plants located at Trombay, Tarapur and Kalpakkam that chemically process radioactive spent fuel discharged from nuclear reactors do not fall under the EIA Notification (BARC 2008).

The EIA process has not been effective, and what has remained is just an empty structure without substance, wherein different agencies go through the motions of putting tick marks in various boxes representing different steps in the EIA process (Ramana and Rao 2010; Rao and Ramana 2008). All nuclear projects, barring one, have received environmental clearances. The EIA reports that form the basis of the clearance have been mostly shoddy, with technical flaws and crucial oversights.[2]

An example of the former is in the EIA for the prototype fast breeder reactor which states that ‘a nuclear explosion … can never occur in a reactor’ (MECON 2000, 8.1). This demonstrates ignorance of the vast literature on the safety of fast breeder reactors which focus on core disruptive accidents.[3] The many oversights in the EIA for the Koodankulam reactors have been detailed in chapter 2.

The nuclear establishment has managed to dominate the EIA process in various ways. Expert committees that recommend whether or not a project should be given environmental clearance always include representatives from the DAE and its allied organizations.[4] Consultants who prepare EIAs have to depend on the nuclear establishment for data on baseline levels of radionuclides and expected levels of radioactive discharges. This allows the latter to be completely in charge of determining the main impact of concern: environmental release of radioactive materials. This is also the case with monitoring the effluents once the project commences. The argument offered for this state of affairs is that all expertise concerning nuclear matters and necessary monitoring equipment is available in the country only within the DAE and its subsidiaries. As such, there is no reason why the MoEF or the pollution control boards cannot invest in monitoring equipment or develop the expertise.

In practically all cases, the overwhelming opinion expressed by participants at public hearings for nuclear facilities has been in opposition to the project. These views have been uniformly ignored by decision-makers. Local administrative authorities conducting public hearings have clearly sided with project proponents, allowing them to dominate the proceedings, denying members of the public the right to present their views, preparing minutes of the meetings that make it appear as though there was little opposition and that project proponents had assuaged any remaining public concerns.

The other component of public consultation involves the project proponent providing written responses to those questions or comments on the EIA submitted at the time of the hearing or through mail or fax to the Pollution Control Board. This is often not followed. When given, the responses are largely unsatisfactory, and sometimes irrelevant.[5] In summary, it is clear that the nuclear establishment treats public consultation as merely a procedural hurdle. Though the public has the appearance of having a voice in the process, it is duly ignored.

The EIA process could be a way for the DAE to improve its decision-making and helping it set public fears at ease. Instead, the DAE's approach has been to comply with the legal requirements to the barest minimum, and avoid them whenever possible.[6] To the extent that legal requirements have been complied with, and the EIA process has been carried out, the quality of the process has been questionable.

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Acknowledgements

The origins of this book go back to over a decade ago, when I was a researcher at what was then the Center for Energy and Environmental Research at Princeton University. Inspired by my colleagues Frank von Hippel, Hal Feiveson and Zia Mian, I applied for and succeeded in obtaining a research and writing grant from the MacArthur Foundation to produce a technical history and assessment of India's nuclear energy and weapons programme. While that idea metamorphosed into a book focused on the folly of India's pursuit of nuclear weapons (*Prisoners of the Nuclear Dream*), which I co-edited with C. Rammanohar Reddy, and a number of technical papers on aspects of the nuclear weapons programme, the goal of examining the nuclear energy programme took much longer.

An important step along the way was joining the Centre for Interdisciplinary Studies in Environment and Development (CISED) in Bangalore, or Bengaluru as it came to be called during my stint there. Much of the research work underlying this book was done during my five years there. I am grateful to the board of CISED and especially its coordinator, Sharad Lele, for the opportunity to work there and pursue my research interests, at some financial and political cost to the fledgling centre. My erstwhile colleagues at CISED, especially Sharad, Ajit, Esha, Shrini, Priya, Sarmistha, Smriti, Arvind, Rinki, Lina, Suhas and Arup, all played small or large roles in shaping the ideas in the book. The administrative staff there—Ganesh, Anand, Jwala, Soumya, Bhanu and Kamalakshi—eased life in many ways.

The stint in CISED gave me the valuable opportunity to interact closely with (the late) Amulya Reddy, who was instrumental in teaching me energy economics and in ceaselessly asking me to ferret out various details on costs associated with the generation of nuclear power so that our calculations could be as rigorous as possible. Amulya's attention to the

ethical issues underlying research while maintaining commitment to scientific integrity and rigour was always a source of inspiration.

CISED also allowed me to benefit from working with two researchers and subsequent friends, Ashwin and Divya, at various points. Both undertook some arduous tasks and performed them cheerfully. Divya meticulously sent out Right to Information (RTI) petitions, filed replies, kept track of dates, appealed denials of information, went through massive documents related to the Kaiga case, and taught me much about the environmental impact assessment (EIA) process. Much of the appendix on the EIA process is based on work with her. Ashwin was instrumental in making me understand many of the details of potential accidents at fast breeder reactors, a task I may never have undertaken on my own. He also exposed me to the wider literature on safety culture. Practically the entire chapter on safety is based on joint work with him.

My friend and collaborator Suchitra has made numerous contributions to this work. Apart from carrying out economic calculations, poring over assorted Department of Atomic Energy (DAE) documents to ferret out cost figures, sending out RTI petitions, appealing denials of information, working with me on multiple drafts of our joint papers and articles, she patiently endured my persistent tinkering with the wording and fact checking of details. Large sections of the chapters on plutonium and economics are based on work with her.

Manju Menon persuaded me to go with her to the public hearing of the environmental impact assessment (EIA) of the proposed Koodankulam III and IV reactors, and Surendra Gadekar took me to the public hearing of the EIA for the proposed uranium mine at Tummalapalle. These hearings turned into first-hand experiences of both the extent of grassroots opposition to nuclear projects and blatant displays of power by the authorities in pushing through such projects. Surendra and Sanghamitra also warmly welcomed me to their home in Vedchhi and generously opened the entire archives of *Anumukti* to me, and this proved an invaluable source of information about the 1980s and early 1990s. Their wealth of experience and their never-say-die attitude has been a source of inspiration. More recently, Suvrat Raju has shared his insights into and analyses of nuclear developments in India, both as part of and outside of articles that we wrote together.

In addition to the collaborators already mentioned, this book has incorporated materials and ideas from numerous articles and papers written with several others, including Praful Bidwai, Antonette D'Sa, Alexander Glaser, Andrew Lichterman, Zia Mian, R. Rajaraman, Dennis Thomas and Susy Varughese. Much of the research and many of the ideas presented in this book have had earlier incarnations in various articles and papers of mine, written individually or in collaboration. Some of the journals and magazines that have published these are the *Bulletin of the Atomic Scientists*, *Daily Times, Dainik Janambhumi*, the *Economic and Political Weekly*, *Energy Policy*, *Frontline*, *Himal*, *The Hindu*, *Hindustan Times*, *InfoChange*, *International Journal of Global Energy Issues*, *Science and Global Security* and *Tehelka*.

A substantial part of this book was written and revised during my stint as visiting fellow at the Program on Science, Technology and Environmental Policy of the Woodrow Wilson School of Public and International Affairs at Princeton University. The final revisions were written when I was with the Nuclear Futures Laboratory and the Program on Science and Global Security, Princeton University. My colleagues here, Chris Chyba, Hal Feiveson, Alex Glaser, Frank von Hippel, Nancy Burnett, and especially Zia Mian, have been great sources of support, information and insight.

This work has benefited over the years from conversations and interactions with many people, too numerous to recall in full. Among them are Itty Abraham, Vineeta Bal, Praful Bidwai, John Byrne, Shantanu Dixit, Antonette D'Sa, Navroz Dubash, Ansar Fayyazuddin, A. Gopalakrishnan, Ramachandra Guha, Vishnu Kamath, Rishikesha Krishnan, Andrew Lichterman, Arjun Makhijani, Manu Mathai, A.H. Nayyar, Anand Patwardhan, Shri Prakash, Sudhir Chella Rajan, R. Rajaraman, Suvrat Raju, Y.B. Ramakrishna, Admiral and Lalita Ramdas, Satyajit Rath, Rammanohar Reddy, (the late) Girish Sant, Raju Sivasankaran, Achin Vanaik, S.P. Udayakumar, and (the late) Dilip Veeraraghavan. My apologies to all those who deserve to be in this list but are not.

Zia and Aparna read through draft versions of the manuscript and provided exhaustive comments. Several others, including Andy, Arjun, Ashwin, Itty, Rishi and Suvrat, read and commented on various specific chapters. Sharon Weiner and Zia brainstormed with me about titles for this book. At Penguin, Sivapriya was instrumental in persuading me to undertake this work and has been a steady source of encouragement over the years as this book took shape. This book has also benefited from Shruti Narain’s careful editing. I gratefully thank all of them. I am, of course, responsible for the remaining errors.

Geetha, my partner for over two decades now, has been an unfailing source of support at home, taking care of our children and the household when I have had to disappear to the office on weekends—and even to a retreat for a week on one occasion—to work on this book. Every so often, I would get a reminder of my incomplete task through her question ‘How is the book going?’ Even as I write this acknowledgement, I can only repeat what I always said, ‘Still going.’

My twin daughters Shruti and Swara contributed in other ways. Their presence and frequent demands for attention ensured that this book never became an all-consuming obsession. I now appreciate the saying in Tamil about realizing the value of the shade only when one is in the hot sun. As I was revising a draft of the concluding chapter, Swara observed that I had far fewer chapters than the Harry Potter books. I agreed with her and she went on to make two predictions: that my book would never be as popular as those books and that it would never be made into a movie. I am afraid she will prove to be accurate on both counts. I hope that my analysis of nuclear power in India is as accurate.

Throughout my life, my parents, S. Mani and Sarada, have given much and expected very little from me. To them, I dedicate this book.

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INTRODUCTION

1. This was the all-India generating capacity as of June 2012. To consider somewhat smaller units, the maximum power demand, presumably during the peak of summer with air conditioners and air coolers running at full blast, in the city of Delhi in June 2012 was about 5.5 GW; the corresponding figures for Chandigarh city and Himachal Pradesh state are 0.3 GW and 2.1 GW (CEA 2012). One GW is a billion watts. One megawatt (MW) is a million watts. A typical electric geyser requires about 2000 watts when operating.
2. There has been much debate on the scale of carbon emissions from the complete nuclear fuel chain. When emissions due to uranium mining, enrichment, transport, waste disposal, and construction, operation and decommissioning of reactors are included, estimates of carbon emissions vary by over two orders of magnitude, from 1.4 to 288 gCO_2e/kWh, with a mean of 66 gCO_2e/kWh (Sovacool 2008, 2957). The range reflects multiple factors, including what are considered and left out, what assumptions are made about the energy inputs into different steps, and the kind of uranium that is mined (Ramana 2009b, 144). Neither of the extreme estimates, the very high or the very low, is likely to be the case everywhere in the near to midterm future.
3. The question of whether the US level of energy consumption was necessary or desirable was not in the realm of discussion. Clearly Bhabha was not persuaded by Mahatma Gandhi's famous admonition: 'God forbid that India should ever take to industrialism after the manner of the West. The economic imperialism of a single tiny kingdom (England) is today keeping the world in chains. If an entire nation of 300 million took to similar economic exploitation, it would strip the world bare like locusts' (Gandhi 1928; Guha 2006, 231).
4. This was the case with the PHWR design that has been adopted as the standard since the 1960s. The problem of pressurized coolant channels sagging and leading to potential rupture and accidents became fully apparent only in the 1980s. It took another decade to be able to develop the means to address the problem.

5. For example, the DAE assumes that the PFBR will operate 75 to 80 per cent of the time at least. However, the only breeder reactor that the DAE has had experience with—the fast breeder test reactor (FBTR)—operated less than 20 per cent of the time during the first twenty years after commissioning (DAE 2006b, 16). The experience with the FBTR lends weight to Admiral Hyman Rickover's summation in 1956, based on his experience with a sodium-cooled reactor developed to power an early US nuclear submarine, that such reactors are 'expensive to build, complex to operate, susceptible to prolonged shutdown as a result of even minor malfunctions, and difficult and time-consuming to repair' (IPFM 2010a, 3).
6. In November 2011, for example, the Secretary of the Department of Atomic Energy publicly stated that the probability of an accident due to a nuclear plant was 'one in infinity' (PTI 2011a).
7. The emergence of this class of nuclear technologists was also the result of a political development. Following the role played by key scientific and technological inventions in influencing the outcome of the Second World War, scientists found that they had much greater access to the State and its resources. Nuclear technology was a particular favourite and, in numerous countries, including India, atomic establishments became extremely powerful in domestic policymaking. This has been best studied in the case of the US (see, for example, Gilpin 1962; Kevles 1995; Evangelista 1999).
8. For discussions on factors contributing to the large share of nuclear power in France, see Fagnani and Moatti 1984; Dickson 1986; Hecht 1994; Ziegler 1995. On the misperceptions about nuclear power there, see M. Schneider 2008.
9. An example is *Nuclear Power in India* (Banerjee and Sarma 2008), which tries, in the authors' own words, 'to give an impartial account of the successes and failures of the Indian nuclear programme'. There is much that is commendable about the book, including some forthright criticism of the DAE, which is all the more remarkable since it was written by two scientists who were associated with institutions that are part of the atomic complex. However, they often stop short at offering the DAE's version of something and contrasting it with that of an independent voice. They do not go the next step and assess which one is

more trustworthy. This is all the more important because the book itself offers numerous reasons to not trust the DAE’s assertions.

10. For example, the number of fuel assemblies in the FBTR is variously mentioned as 22, 23, 25 and 27 in different papers by various heads of the Indira Gandhi Centre for Atomic Research.

1. HISTORY

1. In India, around the same time, there were scientists who were thinking about similar issues. Prof. H.K. Mehta, for example, spoke in 1909 of the phenomenon of radioactivity and of ‘the enormous energy that could be derived from a tiny atom of matter … once the disintegration of matter comes under the control of man’ (ToI 1909, 13). However, he added, ‘for the present, the question has only a scientific interest, as much lacking practical interest as was electricity in the days of Benjamin Franklin’.
2. For socially informed history of science in India in this period see Sur 2011.
3. The Sir Dorabji Tata Trust gave one more grant to Saha’s institute in 1944, but none after that (D. Sharma 1983, 29). It was the same year in which they gave a founding grant to Bhabha’s institute.
4. The earliest reactors were simply piles of graphite blocks with uranium rods emplaced in between.
5. The blankets are made of what are called fertile isotopes. These isotopes do not undergo fission when struck by a low-energy (slow) neutron. Isotopes which can undergo fission upon being struck by a low-energy neutron are called fissile. Materials which have large fractions of fissile isotopes are often called fissile materials, examples being uranium enriched with the uranium-235 isotope or in the uranium-233 isotope. Fertile isotopes can be converted into fissile isotopes by absorbing a neutron and undergoing radioactive decay. In breeder reactors, the rate at which fertile isotopes are converted into fissile isotopes is greater than the rate at which fissile isotopes undergo fission and produce energy.
6. This is done by converting fertile material into fissile materials through the absorption of neutrons.
7. These reactors, like fast breeder reactors, rely on energetic neutrons that have not been slowed down, but fast neutron reactors typically refer to those that do not produce more fissile materials than they use.
8. Madagascar was a French colony then, achieving independence only in 1960.
9. Some of the problems with the use of thorium have to do with reprocessing thorium-based spent fuel and the presence of gamma ray

emitting uranium-232, which is always present with uranium-233 ‘at concentrations ranging from some tenths to hundreds of ppm [parts per million]. This necessitates the manufacture of U-233-based fuels completely remotely in a gamma-shielded environment, a very expensive technique’ (Lung and Gremm 1998, 137).

10. Similar sentiments have been expressed about other forms of power, too. A striking example was about coal written by William Jasper Nicolls (1915), who was involved with the US coal industry for decades: ‘With Coal we have light, strength, power, wealth, and civilisation; without Coal we have darkness, weakness, poverty and barbarism. The most civilized nations of the world are those consuming the most Coal. At the head of these stands the United States’ (6–7).

11. Chairman is the right term for there has never been a woman who headed the Atomic Energy Commission. The majority of AEC chairmen have come from two communities: Parsis and south Indian Brahmins. One quote might reveal something about how important figures in the history of the DAE view membership in these upper strata. In an interview to *Time* magazine in 1955, Homi Bhabha implicitly argued that one of India’s assets in developing nuclear power was its caste structure. ‘Those Brahmans who sit on their bottoms all day,’ Bhabha said, ‘are not just sitting. They are thinking, and they have been doing it for thousands of years. When the young ones turn their thinking to physics, they quickly get rather good at it’ (*Time* 1955).

12. Political scientist Srirupa Roy points out: ‘Until 1996, under the terms of a compulsory exhibition and licensing policy, owners of commercial movie theatres throughout India were required to screen a “state-approved” documentary film or newsreel before the commencement of the commercial feature film’ (S. Roy 2002, 237).

13. NPCIL has entered into an agreement with the National Thermal Power Corporation to form a joint venture that will build nuclear reactors. Its location within this gamut of organizations is not yet clear. Similarly, new organizational forms might be needed in the future if private companies were to enter nuclear power production.

14. Some still persist in terming this a peaceful nuclear explosion and hiding the nuclear weapon-related motivations behind the test. Such semantic evasions are not justified. As early as 1991, Raja Ramanna,

former AEC chairman and leader of the team that conducted the test described it as ‘a prototype weapon’ (Ramanna 1991, 100).

15. Safeguards are accountancy mechanisms to make sure that no fissile material (plutonium or enriched uranium) is diverted to make nuclear weapons. Despite the suggestion implicit in the name, safeguards have nothing to do with enhancing the safety of a reactor.

16. In swimming pool reactors, the fuel elements are placed in a pool of water. The water serves as the moderator and coolant. Some of the neutrons escaping from the core are also reflected back into the core.

17. A reactor, or for that matter, a nuclear weapon, is said to become critical when it can maintain a chain reaction.

18. But this affront did not prevent the United Kingdom’s Atomic Energy Authority from continuing to collaborate with the AEC. For example, it supplied the bulk of the equipment used in India’s first seismic station at Gauribidanur, near Mysore, which is used to detect underground nuclear tests and earthquakes (Mirchandani 1968, 214).

19. The reactor was shut down on 31 December 2010 (Laxman 2011).

20. Isotopes have the same number of protons and electrons, but differ in the number of neutrons. This means that their chemical properties, which are determined by electrons, are identical, but their nuclear properties, or other properties that depend on their atomic weight, might be different.

21. This was one of the three elements in Bhabha’s campaign to develop nuclear weapons capability, the other two being exaggerated claims about how cheap nuclear weapons were, and technical claims about the DAE’s ability to build nuclear weapons quickly (Ramana 2003).

22. For example, the initial financial sanction in 1982 for the Manuguru heavy water plant indicated the project cost as Rs 4.2 billion with a foreign exchange component of Rs 500 million. This was revised to Rs 6.6 billion in 1989, with a foreign exchange component of Rs 786 million (CAG 1994). Similarly, between 1985 and 1993, two foreign consultancy contracts were awarded for ‘various works’ relating to the 540-MW reactors (CAG 1999).

23. This was picked up by Prime Minister Manmohan Singh, who deployed it extensively during the debates over the US–India nuclear deal and, subsequently, over the nuclear liability bill (see, for example, Jacob and Bagla 2006).

24. It was first projected to start operating in 1969 (Tomar 1980, 522), but started commercial operations only in December 1973 (Mittal 2004, 89).

25. RAPS II was originally supposed to come online in 1973, two years after RAPS I (DAE 1969, 80), but it happened only in April 1981 (Mittal 2004, 81).

26. The PREFRE (Power Reactor Fuel Reprocessing) facility was originally scheduled to come online in 1972 (Tomar 1980, 522), but it was only in 1978 that the first trial operations began (DAE 1978, 52). Full-fledged operations involving actual power reactor spent fuel had to wait till 1982 (DAE 1982, 31; 1983, 31).

27. The VII Five-Year Plan ran from 1985 to 1990.

28. Some of the differences in ideology between the BJP and the Congress party, and the relevance of these differences to nuclear weapons are discussed by Achin Vanaik (1997, 2000) (see also Muralidharan and Cherian 1998; Ram 1999).

29. The architect of this change of policy was Manmohan Singh, and his role in reducing budgetary support was subsequently pointed out by many critics of the US–India nuclear deal (see, for example, Ramachandran 2007).

30. Renewable energy sources typically operate for much smaller fractions of the year compared to nuclear power and so their share of actual energy generated would be smaller than their share of generating capacity.

31. Many have, of course, persuasively argued that the 1998 nuclear tests intensified insecurity instead of enhancing security (see, for example, Bidwai and Vanaik 1999; Kothari and Mian 2001; Ramana and Reddy 2003; Rajaraman, Ramana, and Mian 2002).

32. The details are discussed in chapter 2.

33. The details of this projection are discussed in chapter 4.

2. POWER REACTORS

[1] The nuclear establishment has identified new sites in Maharashtra, Gujarat, Andhra Pradesh, West Bengal, Orissa, Haryana and Madhya Pradesh. Other states are also being considered. Two Russian VVER-1000 reactors are already being constructed in Koodankulam in Tamil Nadu.

[2] These modifications are intended to cut costs, and may have safety implications. For example, the size of the pressure vessel will be reduced (Jagannathan 2009b). The pressure vessel is meant to withstand the shock that might be caused by an accident that might release a large amount of energy within the core of the reactor. Any reduction in the size of this vessel implies that the internal pressure generated during any given accident would increase, making it more likely that the vessel would fail.

[3] For example, according to the International Atomic Energy Agency’s PRIS database, the load factor of the Kakrapar I reactor started a steady climb up from 53 per cent in 1997, reaching its highest value of 97 per cent in 2003, and then decreasing steadily to less than 30 per cent in 2008.

[4] For example, compare pages 140, 152, and 159 of GoI 2007. They offer an indication of the general sloppiness found in many DAE documents. One might gain some appreciation of the significance of the difference between the two figures by noting that the annulus between the two circles has an area of 0.94 sq. km that could be home to about 260 people at the population density implicit in setting a maximum size of 20,000 people within a 5-km radius of the plant.

[5] Several thousand people from outside the exclusion zone who were judged to have received high radiation doses were also evacuated (UNSCEAR 2000, 473).

[6] Only in the 1980s were there audacious, though ultimately wrong, projections of nuclear power becoming competitive with coal-based thermal power at the mine pithead itself (M.R. Srinivasan 1985, 17).

[7] The reference is to the title of an essay by Arundhati Roy (1999) on the Sardar Sarovar Project and the general problem of displacement by development projects.

8. The reactor was supplied to an electric utility consortium led by Chicago’s Commonwealth Edison.

9. In return, USAID stipulated that US companies and consultants be hired for the project (Chaudhuri 1972). Other accounts claim that the loan amount was $72.7 million (see, for example, S. Dasgupta 1981).

10. The latter union was led by George Fernandes, who was to become India’s defence minister at the time of the 1998 Pokhran nuclear weapons tests.

11. It is, of course, possible that the United States would have done so even without the Bechtel connection.

12. A relative of mine used to work at that time as an engineer in TAPS. He has recounted that on many occasions there would be phone calls from various high-level political officials asking the plant personnel to restart the reactor. He recalled one phone call where the person on the line was none other than Prime Minister Indira Gandhi herself who asked him to restart the plant quickly (‘jaldi’).

13. Secondary steam generators are heat exchangers where the hot coolant fluid that is carrying away the heat produced in the reactor core transfers the heat to water in a secondary circuit and converts it into steam. In pressurized reactors (PWRs or PHWRs), such a secondary circuit is essential because the coolant always has to remain in a liquid state and cannot drive a turbine. In a BWR, however, it is not essential to have this secondary cycle, and there are designs with both one and two cycles. Over the decades, the dual-cycle designs have become less popular.

14. Unlike natural uranium that has only about seven parts in thousand of the uranium-235 isotope (the remaining 99.3 per cent being uranium-238), the fraction of uranium-235 is on an average about 2.44 per cent in TAPS fuel (Katiyar and Bajaj 2006, 882). Since then, the DAE has set up a uranium enrichment facility in Rattehalli, Karnataka, but even as of now it may not have sufficient capacity to enrich the quantities of fuel required to run TAPS 1 and II at reasonable load factors (Ramana 2004).

15. See Appendix 1 for details.

16. The contamination of the fish may or may not be significant, but the perception that it is unsafe to eat has a very real impact on the livelihood of the fisherfolk. This is an example of what has been termed

technological stigma by social scientists (Gregory, Flynn, and Slovic 1995; Slovic, Flynn, and Gregory 1994).

17. The reactor did not operate for long; in July 1989, the reactor was shut down due to noise pick-up by the reactor protection logic, and the unsatisfactory operation of the speed control system for primary sodium pumps (CAG 1993).

18. To put that into perspective, the allowed dose for nuclear workers in an average year is 20 millisievert. So, in one hour, a worker could be exposed to the maximum permitted for forty-five years of work.

19. The FPC report is the official document that has put up the largest potential for nuclear power in the country. The document estimated that the potential power capacity of the uranium reserves of the country, if used in breeder reactors, could be between 600 GW to 1000 GW (yes, gigawatts!). It went on to state that if thorium were used, ‘there will be virtually no limit to the capability to generate electricity from the resources point of view’ (FPC 1974, 28–29).

20. Breeder enthusiasts, of course, maintain that the Superphénix was a success and that it was shut down for political reasons. See, for example, the interview with Georges Vendryes, honorary vice-president, French Atomic Energy Commission (Subramanian 2006a). In view of the operating history presented here and elsewhere, that assertion rings hollow.

21. As explained in chapter 7, this has major consequences for catastrophic accident possibilities in the reactor.

22. This is discussed further in chapter 6.

23. A capital-intensive source of power requires large amounts of capital investment, and the cost of generating electricity is dominated by the cost of the capital.

24. Note that, at the time Sarabhai was discussing this, all nuclear costs were essentially projections since no nuclear electricity had actually been generated in India.

25. PHWRs can be fuelled while they are operating, but LWRs, such as TAPS I and II, cannot.

26. Another technical reason for such small capacity plants is that if a large fraction of the grid capacity was to go down suddenly, there would be voltage and frequency disruptions.

27. At the Eleventh Session of the IAEA General Conference in 1967, Sarabhai moderated a panel discussion where Weinberg presented his ideas on the subject.

28. For more on this argument, although in a different context, see Flank 1993.

29. This is true not only of India, but elsewhere as well. For example, around the same time, in a country that was yet to set up a single nuclear reactor, Iranian scientists were exploring the techno-economic feasibility of setting up a nuclear-powered agro-industrial complex in the south desert coastal region of Iran, focusing in particular on desalinating water as a way to sell the idea of nuclear power to a country overflowing with oil and natural gas (Jalali-Mossallam 1970).

30. During this earthquake, the peak ground acceleration was 2.5 times greater than what was assumed as possible for the 'extreme design earthquake'. This discrepancy testifies to the problem of not being able to predict the magnitude of earthquakes with reliability (Ramana and Kumar 2007).

31. The use of snubbers is not without problems. They require frequent maintenance and may not always function as designed. In particular, mechanical snubbers may get 'locked' and hydraulic snubbers may leak and, hence, may not work when required (Parulekar et al. 2004).

32. ECCS, the Emergency Core Cooling System, is a safety system that is supposed to inject large amounts of water into the reactor core in the event of an accident where the core threatens to overheat and melt. The DAE's reactor design relies on the ECCS as a safety measure (RSAG 1986, 23). But without integrated testing, it would not be clear whether the system would work as designed in the event of an accident. According to the AERB the integrated test showed certain deficiencies, but these were subsequently rectified (AERB 1993, 5).

33. A member of DAE was present at the founding conference of WANO in Moscow in 1989 (M.R. Srinivasan 2002, 193).

34. One famous example is the hydrogen bubble that appeared within the core of the Three Mile Island reactor during the disastrous accident of 1979. This had not been entirely foreseen. Once formed, there was considerable confusion for several days, despite the engagement of the

foremost experts in the field, about when there would be sufficient oxygen to allow for an explosion.

35. NPCIL is also constructing RAPS VII and VIII based on the same design.

36. Nagarjunasagar and Kovvada in Andhra Pradesh were selected as potential sites for nuclear reactors, but there were no concrete plans to construct reactors there (Venugopal 1988, 1831; *Nuclear India* 2000). One reason for the DAE's reluctance might be the Naxalite insurgency (Gadekar 2008).

37. Vishnu Kamath now teaches chemistry at Bangalore University.

38. Unfortunately, later judgements by the Supreme Court have essentially rejected this position (Ramana 2009a).

39. For example, four of the 220-MW plants—Kaiga I and II and RAPS III and IV—included in the profile had been allotted Rs 1578.40 crore, but 'NPCIL incurred an expenditure of Rs 3586.30 crores till 1997–98' (CAG 1999).

40. Besides the Bhoothathankettu (Kothamangalam) site in central Kerala that has already been mentioned, there was a proposal to construct a nuclear reactor in Peringome in northern Kerala but that, too, had to be abandoned due to public protests.

41. Unlike the Chernobyl reactor which was of the RBMK design and used graphite as moderator, the VVER-1000 is an LWR and uses water as moderator. It does not share some of the drawbacks in safety measures that are inherent in the RBMK design, such as the positive coolant void coefficient and the lack of a containment dome. Both reactor designs have antecedents that date back to the early days of the nuclear power programme in the Soviet Union, with the former design having been used first for plutonium production for nuclear weapons and the latter design having first been developed to propel nuclear submarines (Josephson 2000).

42. The first VVER-1000 reactor at Kalinin in Russia had started operating only in 1984.

43. This was the period when many reactors were experiencing high cost overruns.

44. One reason given was that NPCIL had acquired more land than was necessary for constructing the first two units (*Hindu* 2000).

45. NPCIL did have to prepare an EIA, which it did in 2003. But this was never released to the public till the massive protests that erupted in 2011–12. In early 2012, as part of an effort to make itself seem more transparent, NPCIL finally put up the EIA on its website.

46. NPCIL had commissioned an EIA study for four reactors but it had an in-principle approval for only two 1000-MWe LWRs from the DAE, that is, Koodankulam III and IV. NPCIL followed this by filing an application to the Tamil Nadu Pollution Control Board for constructing four reactors (DC and DEE 2007). In June 2007, NPCIL applied to the ministry of environment and forests (MoEF) for environmental clearance for Koodankulam Units III to VI. Citing the absence of prior approval from the DAE, the Expert Appraisal Committee considered only Units III and IV of the proposal (MoEF 2007). It is not clear whether NPCIL is going to go through a clearance process for two more reactors.

47. Yet another significant omission in the EIA is its neglect of the possibility of a severe ('beyond design basis') accident of the reactor, leading to a massive release of radioactivity into the environment. The EIA shows no evidence of being aware of the widely expressed concerns about the safety of VVER-1000 reactors, in particular, the reliability of the control rod mechanism. The EIA does not mention the likely ranges of radioactive contamination or the emergency preparedness plans that have to be circulated in the event of an accident so that people may know how to mitigate the impact of such a contingency.

48. This was formerly available at WIKILEAKS.ORG/CABLE/2007/03/07MUMBAI134.xhtml#. However, the WikiLeaks website that hosted all the cables has been subject to severe cyberattacks on numerous occasions and was not available at the time of this writing.

49. In 2006, a DAE site selection committee visited a number of coastal areas in the country and identified sites in Andhra Pradesh, West Bengal, Gujarat and Orissa (Sasi 2006; Wadke and Subramanian 2007). The identified sites were, reportedly, Kovvada in Andhra Pradesh, Haripur in West Bengal, Mithi Virdi in Gujarat and Pati-Sonapur in Orissa (Agrawal 2007; *Telegraph* 2006; R. Shah 2008; Mohapatra 2007).

50. NPCIL seems to be in denial, or ignorant, of this fact. In the reply to a Right to Information request from Dr B.J. Waghdhare, the central public

information officer (CPIO) of NPCIL stated categorically that the 'proposed Jaitapur site is not earthquake prone'. At a public meeting in the collector's office in Ratnagiri on 10 August 2007, the project director of the Jaitapur nuclear power project said that the project site was located in earthquake zone III (Gadekar 2007). When someone present pointed out to him that the site was located in earthquake zone IV, he asserted that zone IV was less dangerous than zone III. It was only after he was shown a map where zone IV was shown in bright red while zone III was in light pink that he withdrew his absurd assertion.

51. The area around Haripur was reported to have a 'high crop yield and very high cropping intensity', with 'exceptionally high' paddy yields, and to be capable of producing a variety of vegetables and fruits, and with 'hundreds of water bodies for prawn culture and sweet water pisciculture'.

52. The claim about safer technology is hard to evaluate. As discussed in chapter 7, there are always legitimate doubts about the completeness of calculations which seek to establish a quantitative estimate of the probability of a nuclear accident. Further, when compared to the early reactors that were being constructed at the time that the site selection criteria were laid out, modern reactors are of much greater capacity. For example, the Tarapur I and II reactors had an operating power capacity of 380 MW. Even a single VVER-1000 would have roughly two and a half times as much radioactive material in its core when operating.

53. A US Department of Energy study of water requirements for different kinds of thermoelectric power generation showed that nuclear power has one of the highest requirements for cooling water (NETL 2006).

54. Many of these movements also end up, willy-nilly, being anti-globalization struggles because many of the key players in setting up these projects are multinational corporations. This is an example of how 'the ecological debate overlaps in many ways with the globalization debate' (Moore 2000, 123). More generally, see Harvey 2003 (chap. 4) and Klein 2001.

1. For a list of strategic reactors and their potential fuel requirements see Mian et al. 2006 (16–22).
2. Export to other countries was part of the Commission's considerations according to M.G.K. Menon, former director of the Tata Institute of Fundamental Research (Bhatia 1979, 85). The example of Bhabha trying to obtain heavy water through such means has been mentioned in chapter 1.
3. This was similar to what the United States Atomic Energy Commission (USAEC) had started doing earlier. The USAEC's programme of subsidies for uranium exploration, development and production was 'unprecedented within the mining industry. For example, the [USAEC] paid out close to $2,500,000 for discovery bonuses from 1948–53, established minimum uranium prices for a period of ten years, and built over 300 miles of roads' (Paehlke 1995, 656). Beryl is the most important mineral containing the element beryllium, which had applications in nuclear research as well in assorted military equipment.
4. In the United States, the US Atomic Energy Commission and the Geological Survey published a booklet in 1951 on prospecting for uranium (Barnes 1956, v).
5. There is no evidence that there was any thought given to the potential dangers to the health of the people living in the neighbourhood.
6. The latter clearly seems to be based on something submitted by the DAE, and is incorrect. Each 1000 MW of PHWR capacity requires about 144 tonnes of uranium per year at 80 per cent capacity. Thus, the identified conventional resources can support over 24,000 MW of PHWRs.
7. In the case of Banduhrang, for example, it was estimated that 5000 people were expecting displacement (Mahapatra and Jayan 2004).
8. According to an article in *Ranchi Express* on 31 August 2005 cited in http://www.wise-uranium.org/upin.xhtml

1. But, as a friend of mine remarked upon hearing this, ‘Unfortunately, the food that this vessel serves is toxic and radioactive. And it is very expensive.’
2. In other words, its calculations do not include enough time for a certain amount of plutonium to become usable for refuelling the same reactor or setting up new breeder reactors. When I presented this work at the Annual Meeting of the Institute of Nuclear Materials Management in Baltimore in July 2010, a member of the audience confirmed that the British nuclear establishment had committed similar errors when it made projections of breeder growth.
3. Even if the reactor fuel does not initially contain plutonium, some of the neutrons produced during fission are absorbed by a fertile isotope of uranium, uranium-238, to produce plutonium. Some of this plutonium also undergoes fission.
4. The PUREX process has many safety concerns, which we do not explore here. One particular concern is the possibility of the formation of a chemical mixture called red oil, which forms when an organic solution comes into contact with concentrated nitric acid at temperatures above 120 degrees Celsius, and a resulting runaway reaction (DAE 2011, 90).
5. The tanks contained about 70 to 80 tonnes of highly radioactive waste with a total radioactivity content of 20 million curies (Cochran, Norris, and Bukharin 1995, 109–13). The energy generated by the explosion has been estimated to be between 70 and 100 tonnes of TNT-equivalent. The collective radiation dose (see Box 8.1, chapter 8) resulting from the accident was nearly 6000 person-Sv, which would result in about 300 cancer deaths. The fallout settled along a 400-km long swathe of land, covering an area of over 20,000 sq. km (Stone 1999).
6. Some uranium ores contain up to one part per trillion of plutonium.
7. Israel was also acquiring the technology to reprocess spent fuel from France around the same time. In contrast to the DAE’s public advertising of the Trombay plant, there was complete silence about this acquisition in Israel. As Avner Cohen, author of the definitive history of Israel’s nuclear programme, observes, ‘the most sensitive and secret aspect of the

agreement [with France] was the reprocessing plant, to which there was no reference in the official documents' (Cohen 1998, 59).

8. In 1987, P.K. Iyengar, who was to go on to head the DAE, wrote that 'a plant with 400 t capacity is planned to become operational by mid-1990s to receive spent fuel from Narora and Kakrapar reactors. It is envisaged that another 400 t capacity-plant would have to be suitably located for reactors beyond Kakrapar to bring the total reprocessing capacity to 1000 t by 2000' (Iyengar 1993, 83). Neither of these plants has been built nor was the reprocessing capacity target reached.

9. The mass refers to the heavy metal content of the spent fuel and, hence, the capacity of reprocessing plants is sometimes expressed as tHM/y.

10. On 31 March, the first test rods were inserted, followed by radioactive fuel rods on 1 June; the reprocessing of the spent fuel from the CIRUS reactor started on 18 August (Mirchandani and Namboodiri 1981, 71).

11. This is according to Raja Ramanna, who was to become chairman of the AEC. But, Ramanna lamented, this offer was not utilized. That should come as no surprise, though, for no country in South East Asia had any operating nuclear reactors.

12. The burn-up is the amount of thermal energy produced per unit of uranium.

13. The history of how the NNPA was applied to India and the intense negotiations that followed this application is recounted by George Perkovich (1999, 205–09).

14. See DAE 1992a, 2.24; 1995a, 2.2; 1996a, 18; 1998a, 2.2; 2005a, 37.

15. KARP was reported to have undergone major modifications starting in 2004 (DAE 2005a, 38); this process was reportedly completed and the plant restarted in March 2009 (S. Banerjee 2009). This would have likely involved the process of switching from one line to another. Reprocessing, by its very nature, uses harsh chemicals and deals with extremely radioactive materials, and hence plants do not have long lifetimes.

16. We are told, for example, that the 'exchange tower for the Baroda [heavy water] plant was of a mammoth size, about 30 metres long, [with] an outer diameter of 2.5 metres and weighed 530 tonnes' (Sundaram, Krishnan, and Iyengar 1998, 129).

17. Presumably, Kupp was contrasting this in his mind to the far more mechanized and less labour-intensive forms of construction prevalent in

the United States.

18. The estimated cost of KARP has been variously mentioned in DAE documents over the years as Rs 1.74 billion (DAE 1987b, 41), Rs 2.65 billion (DAE 1991b, 37), Rs 2.95 billion (DAE 1992b, 37), Rs 3.51 billion (DAE 1993, 29) and Rs 3.78 billion (DAE 1995b, 35). The final figure comes down abruptly to Rs 1.43 billion (DAE 1999, 81).

19. It was not an easy or quick task. Even though performance budgets are in principle publicly available, there is no library or documentation centre that seems to have a full collection of these. We had to borrow and copy these documents from at least seven public and private libraries, spread out over five states in India and the Library of Congress in the United States.

20. This figure does not include any interest due to construction component for two reasons. First, KARP has been constructed by the DAE and financed by the government, which does not seem to have charged any interest. Second, we were interested in exploring the inherent economical viability of reprocessing and plutonium-based reactors, and including an interest-based component would make this dependent on the financing package.

21. This is a life-cycle cost and is obtained by dividing the sum of all the costs over the entire (assumed) lifetime of the plant, discounted to the reference date, by the sum of the quantities of spent fuel reprocessed, again discounted to the reference date. The discount rate and its choice are discussed in chapter 6.

22. The assumption may be optimistic and experience at DAE-run reprocessing plants appears to indicate a higher rate of losses, closer to 3 per cent (Tongia and Arunachalam 1998, 552).

23. This is the ratio of the fissile material produced to the fissile material consumed by the reactor during any fixed period of time.

24. The breeding ratio is increased by eliminating material that could slow down the neutrons.

25. Grover et al. (2006) state explicitly that they assume ‘that the technology of Pu–U metal-based FBRs having the fissile growth rate of 8.1 per cent/yr … would have been developed by 2020’ (2846).

26. It appears that the DAE has not been able to come up with a fuel design that can reproduce such a high breeding ratio; the most they seem to have

achieved is a metallic fuel design whose breeding ratio 'is calculated to be 1.45' and is 'being studied' (B. Raj 2009, 146).

27. Even in the DAE's projections, the bulk of the generation will continue to be coal-based thermal power, which is predicted to go up from about 72 GW in 2002 to 615 GW in 2052. Other fossil fuel–based generation capacity is projected to go up from about 33 GW in 2002 to 204 GW in 2052. Despite the incredible and massive increase of nuclear power, the country's carbon emissions are also projected to increase drastically.

28. All this assumes that MFBRs operate at 75 per cent LF, the same assumption as the DAE has adopted.

29. This is not the case with LWR or PHWR spent fuel.

30. For more detail on the assumptions behind this estimate, see IPFM 2010b.

31. The bulk of the plutonium in the spent fuel from nuclear reactors is plutonium-239. However, if the fuel elements stay in the reactor for longer periods of time, some of this plutonium-239 absorbs a neutron, becoming plutonium-240. This could, in turn, become plutonium-241, and so on. The presence of plutonium-240 makes it possible for a nuclear weapon to disperse before the optimal design yield of explosive energy is produced. Thus, it creates the potential for a nuclear weapon to explode with a reduced yield, what is called a fizzle.

32. The International Commission on Radiological Protection estimates that only 0.05 per cent of ingested plutonium is absorbed by the gastrointestinal system (ICRP 1994, 127).

33. The rate at which ionizing particles impart energy locally to a medium is known as the linear energy transfer, commonly abbreviated as LET. The damage to living tissue by absorption of a given amount of energy is generally greater as the distance over which this energy is imparted decreases, that is, as the LET increases (Shapiro 1990, 34).

34. This estimate may be fairly conservative as it ignores the large fraction of non-fatal skin and thyroid cancers.

5. HEAVY WATER

1. Chatterjee and Gupta 1993 (201) cited in Shukla 2006 (201).
2. The now-dismantled plant at Nangal used a third method called the electrolysis process.
3. The agreement with the IAEA for safeguarding the heavy water from the Soviet Union (INFCIRC/260) was signed on 17 November 1977 and the text is available at http://www.iaea.org/Publications/Documents/Infcircs/Countries/india.shtml (accessed 10 October 2012).
4. See DAE 1994; 1995a; 1996a, 16; 1997a, 3:8.
5. The lease rate used to be 12 per cent per year earlier but was lowered some years ago; according to the DAE, the reduction was one of several measures to make ‘nuclear power tariff competitive’ (DAE 2005b, 34).
6. In December 2011, Heavy Water Board Chairman Rajnish Prakash declined to disclose the quantity of surplus heavy water available for sale or how much of it is produced in the country saying, ‘These are strategic questions I cannot answer’ (K.S. Jayaraman 2011).

6. ECONOMICS

1. This is the exact version of the quote widely rendered as ‘Nuclear power, once claimed to be too cheap to meter, is now too costly to matter.’
2. In private, DAE officials may, on occasion, be more forthright. In 1985, while speaking at a meeting of members of the Indian and French nuclear establishments, one of the leaders of the DAE’s internal Committee for the Pricing of Nuclear Power was candid enough to reveal that ‘a major objective of the nuclear community in India is to ensure that not only is the physical target of nuclear growth achieved but that its full potential of favourable economics and costs is also fulfilled. That would be a historical achievement in the sphere of high technology in the developing world’ (J.C. Shah 1985, 369). In other words, favourable economics was not something that was inherent to nuclear power, but a goal that was to be fulfilled. As with much else characterizing this future-tense technology, its economics has not been favourable so far and there is no reason to believe that it will be so anytime soon.
3. Therefore, as the Nuclear Energy Agency (NEA) of the Organisation for Economic Co-operation and Development (OECD) points out, because of the risks faced in competitive electricity markets, ‘investors tend to favour less capital-intensive and more flexible technologies’ (NEA 2005a, 16).
4. At the time when the analysis was carried out, these were the most recent.
5. Anthropologist Arturo Escobar describes the strategy thus: ‘The aim of all the countries that emerged with this new status [that is, underdeveloped] in the global concert of nations was invariably the same: the creation of a society equipped with the material and organizational factors required to pave the way for rapid access to the forms of life created by industrial civilization. Articulated around a fictitious construct (‘underdevelopment’), a discourse was produced that instilled in all countries the need to pursue this goal, and provided for them the necessary categories and techniques to do so. This discourse emerged and took definite shape between 1945 and 1955, in the climate of the great postwar transformations, drastically altering the character and scope of

the relations between rich and poor countries and, in general, the very perception of what governments and societies were to do' (Escobar 1988, 429).

6. Nuclear technology, as an emblematic modern technology, does indeed fit the pattern recognized by political scientist Nicholas Xenos, who has argued that the binary opposites—abundance and scarcity—exemplify the condition of modernity (Xenos 1989).

7. In fact, it has been argued that assumptions about future nuclear costs should encompass not only the distribution in costs but also the uncertainty in the very distribution (Hultman and Koomey 2007, 3).

8. By the 1960s, the figure was quantified as '600 miles from a coalfield' (AEC 1970, 5).

9. Bhabha's predictions of how much nuclear generating capacity could be installed also had resonance with British projections. At the 1955 Geneva conference (see chapter 1), the UK delegates announced that the country planned to install 2 million kilowatts (or 2000 MW) by 1965 (Bupp and Derian 1978, 15). Speaking at the First Special Session of the IAEA General Conference in 1957, Bhabha claimed that 'it was technically possible to instal equipment producing one million KW of atomic power by 1965' (Jain 1974, 81).

10. Decades later, the same motivation was one factor in Prime Minister Margaret Thatcher choosing nuclear power over coal. She chose a prominent nuclear engineer to head the country's Central Electricity Generating Board. He became one of her chief allies in 'her brutal and legendary fight against the powerful National Union of Mineworkers and its militant leader, Arthur Scargill' (Cooke 2009, 351). Unfortunately, the enthusiasm for nuclear power conflicted with Thatcher's espoused preference for the free market. Ultimately, the market won.

11. The higher value translates to a little under Rs 10,000/kg at 2002 prices, which can be compared to the reported cost of Rs 16,454/kg (Subramanian 2002, 85).

12. This turns out to be approximately Rs 2 million/kg in 2011 rupees.

13. In 2009, for example, AEC Chairman Srikumar Banerjee exhorted BARC employees to 'fulfil our cherished dream of providing long-term energy security to the country by utilizing our vast reserves of thorium after establishing a substantially higher capacity of nuclear power' (S.

Banerjee 2009). Note that the utilization of thorium is to be done ‘after establishing a substantial higher capacity’, rather than soon.

14. The joint chairman of the committee was Walker Cisler, another nuclear promoter. Cisler was president of the US Detroit Edison Company that was, around that very time, operating the Fermi breeder reactor which suffered a disastrous accident in 1966. The accident inspired a book by journalist John Fuller (1975) and a song by the musician Gil Scott-Heron, both titled *We Almost Lost Detroit*.

15. The problems with the DAE’s handling of heavy water costs are discussed in chapter 5.

16. The MAPS I reactor’s capital cost was taken as Rs 1158.4 million and its capacity as 235 MW while the Singrauli plant at that time comprised three 200-MW power plants at a cost of Rs 3037.5 million. Both the figures for the MAPS I plant proved somewhat incorrect: its final cost was Rs 1188 million (DAE 1996c), and the reactor’s power output varied between 150 MW and 220 MW, with values below 200 MW for at least sixteen years (IAEA 2012).

17. The busbar is the point which connects the generating unit and the larger electricity grid. Transmission and distribution costs are external to the production process itself and their inclusion would make the comparison dependent on the locations of the power plant and the load centres.

18. The concept is described in chapter 2.

19. Even ignoring the time value of money, this is inconsistent because it adds rupees from different years without considering differences in purchasing power due to inflation.

20. Parthasarathi’s account also implies that the costs of health and safety of personnel, waste handling and disposal, and decommissioning of the reactor were not included.

21. The discount rate used here can be either a nominal discount rate d_n or a real (that is, inflation corrected) discount rate d_r with the two options being related as: $d_r = (d_n - i)/(1 + i)$ or approximately $d_r = (d_n - i)$.

22. There are also contributions to the total costs from expenditures that are made before the actual construction begins, for example, the advances

paid to manufacturers of equipment that require a long lead time and various pre-project activities.

23. The process of constructing the plant and manufacturing the various components is energy-intensive and, hence, during this period, the plant actually acts as a sink for energy. This is, of course, compensated for by electricity generation during the economic lifetime of the plant, but the net energy balance changes with the period of construction.

24. The debate about the choice of discount rate is most intense when it comes to costs that are borne by future generations, for example, those costs that have to do with the disposal of radioactive waste that remains hazardous to human health for hundreds of thousands of years. Choosing a large discount rate would mean that future expenditures are given very little weight in economic calculations. Some economists have proposed that in the interests of intergenerational equity, such activities should be valued at a zero or a very low discount rate (Howarth and Norgaard 1993). One approach that has been suggested to deal with this problem is to use two discount rates, one for short-term expenditures and a lower one for long-term expenditures (Charpin, Dessus, and Pellat 2000). Such an approach would increase the cost of the waste-disposal component in nuclear generation. Within the Indian context, such debates and long-term considerations have not played any role in determining electricity policy.

25. Farber deliberately chose the period before the 1979 Three Mile Island accident to avoid the possibility of its having affected stock prices.

26. The underlying reason was neatly laid out by Peter Bradford, a former member of the US Nuclear Regulatory Commission, who told the *New York Times*: ‘The abiding lesson that Three Mile Island taught Wall Street was that a group of NRC-licensed reactor operators, as good as any others, could turn a $2 billion asset into a $1 billion cleanup job in about 90 minutes’ (Wald 2005).

27. I thank Prof. R. Srinivasan of IIM, Bangalore, for pointing this out and for calculating the increase in discount rate on account of the higher risk.

28. This was at 1997–98 price levels.

29. The DAE typically constructs two nuclear reactors at one time at each site. That is why the two reactors are treated as one unit.

30. For details see Ramana, D’Sa, and Reddy 2005.

31. As discussed in chapter 4, the cost of reprocessing spent fuel is substantial.

32. In line with current government policy, we did not impute any economic costs for the air pollution resulting from coal-based thermal plants. Though such pollution has gained in policy relevance with the heightened concern about global warming, the inclusion of pollution costs remains problematic for many reasons, especially in the context of a comparison with nuclear power. This is because the pollution externalities for nuclear power are difficult to quantify for many reasons. Two proximate ones are the scientific and political controversies surrounding the health impacts of low-level radiation and the lack of reliable data on radioactive emissions from nuclear facilities and the impossibility of independent verification of the scarce data available in the Indian context (Ramana and Gadekar 2003; Ramana 2009a). Finally, unlike carbon dioxide which has substantial sinks in the terrestrial and marine ecosystems, there is no way to render radioactive materials benign. Hence, the environmental and public-health impacts of long-lived radioactive wastes could occur well into the future, possibly tens of thousands of years from now. There are inherent problems with quantifying these. Thus, it is all but impossible to make a fair comparison of environmental externalities between coal power and nuclear power.

33. The 12 per cent was determined by averaging the auxiliary consumption figures for all nuclear reactors in the country. These were reported to be 13.4 per cent, 12.4 per cent, 11.5 per cent, 11.3 per cent, 12 per cent, 11.7 per cent and 11.9 per cent for the years 1994–95, 1995–96, 1996–97, 1997–98, 1998–99, 1999–2000 and 2000–01 respectively (DAE 1997b, 10; 1998b, 14; 1999, 12; 2000a, 13; 2002b, 27).

34. For example, in 1983, the AEC quoted a price of Rs 3,875/kg whereas CAG had calculated that it should be Rs 13,800/kg (A.K.N. Reddy 1990, 22).

35. Our estimate was in the same ballpark as the 1983 figure of Rs 6,635/kg (Rs 26,960/kg when inflated to 2002 prices) cited by the then head of the DAE (Ramanna 1985).

36. This had to be done without my collaborators because of ill health and the unfortunate death of one of my co-authors (Amulya Reddy) during this period.

37. The details of the latter are in chapter 5.

38. An additional reason that has become apparent is that the Kaiga I and II reactors have not managed the 80 per cent load factor that we, and Thakur, had assumed. As of August 2010, their lifetime load factors were 66.8 and 67.4 per cent, respectively. Likewise, the Raichur plant has also managed only lower load factors, roughly 70 per cent in some years. If the levelized cost of both nuclear power and coal power are reckoned with a 70 per cent capacity factor, then the crossover rate for Kaiga III and IV with RTPS VII will be under 4.5 per cent, lower than the 80 per cent case, because of the capital intensity of nuclear power.

39. The details of this projection and its methodological problems are discussed in chapter 4.

40. The DAE has typically dismissed the relevance of countries like the United States, United Kingdom and Germany cancelling their breeder programmes. In a magazine interview, the director of IGCAR confidently declared: ‘When the oil price shoots to $100 a barrel, many countries would scramble for breeder reactors’ (Subramanian 2004a, 104). This is misleading on two counts. Technically, oil and nuclear power do not serve similar energy needs; oil is largely used for transportation and, occasionally, peak electricity generation. Nuclear power is used only for baseload electricity generation. Economically, it has been argued, one ‘predictable consequence of continued oil price rises is general economic inflation. Another is recession. It is doubtful that such macro-economic conditions are congenial to the rapid growth of a highly capital-intensive technology with pay-off lead-times of a decade or more’ (Bupp 1981, 75). Finally, even though oil prices went over $100 a barrel by 2011 there has been no ‘scramble for breeder reactors’.

41. This claim, implausible though it might seem, is actually far more modest than what Bhabha had claimed, and that, too, for the even more futuristic thorium–uranium-233 breeders. Bhabha estimated that the ‘total capital investment in these breeder power stations, including the cost of inventory in fuel and blanket, is estimated to be under Rs 1400 per kilowatt’ (Bhabha 1958, 407). In contrast, Bhabha’s estimate for the capital investment for natural uranium–powered reactors, that is, not breeders, was Rs 2400 per kilowatt. This assumption that breeder reactors would be cheaper has proven to be utterly misguided.

42. In line with the DAE’s philosophy of not treating spent fuel as waste, we did not include the cost of dealing with this highly radioactive material; however, in the case of the PFBR, the cost of reprocessing its spent fuel is indirectly included in the fuelling cost.

43. This does not include the expenditures on the PFBR prior to 2004, which amount to 1.24 billion in mixed year rupees.

44. Construction costs for the French Phénix reactor totalled (1974) FF 800 million ($800 million in 2004 dollars) or $3200/kW (IPFM 2010a). However, a further 600 million ($870 million in 2004 dollars) were spent on Phénix upgrades between 1997 and 2003. The 1240-MW Superphénix was far more expensive with an initial investment of (1985) FF 28 billion ($4.9 billion in 2004 dollars) (NUKEM 1997, 15). The 300-MW Kalkar reactor in Germany cost (1985) DM 7 billion ($3.6 billion in 2004 dollars) (Neffe 1985).

45. Another reason to stick with the DAE’s estimate is that similar cost overruns would presumably afflict the PHWRs under construction as well.

46. According to the PFBR design, the reactor has to be refuelled after 180 Effective Full-Power Days of operation (Sodhi et al. 1995). What that means is that if the reactor were operating at full power at 100 per cent efficiency, then, it would have to be refuelled every 180 days. If the reactor were to operate at a 75 per cent capacity factor, this would have to be done somewhat less frequently: about eight months. At this capacity factor, the PFBR requires a little over one tonne of plutonium per year as fuel (Glaser and Ramana 2007, 94). The fuel that is removed from the reactor would be very hot and radioactive. Therefore, it would have to be cooled. As per the design, the spent fuel is stored within the reactor itself, where the liquid sodium would carry away the heat produced, till the reactor is opened up for refuelling, after eight months. The spent fuel would still be hot and radioactive, and would have to be stored in a pool after all the sodium sticking to the spent fuel is washed so as to avoid its reacting with water (Chetal et al. 2006, 857). Based on the FBTR experience, we assumed that the spent fuel from the PFBR is stored under water for an additional sixteen months outside the reactor to arrive at a total storage time of two years. After this, the spent fuel has to be reprocessed, the plutonium extracted and fabricated into fuel, and

transported back to the PFBR. All this should take at least another year. In all, the total time between the time that the fuel is removed from the reactor core and when it reappears as a fresh fuel rod is three years. This means that, for at least the first three years of operation, the PFBR will require plutonium from KARP.

47. At 75 per cent capacity factor, assuming a loss of 1 per cent each at the reprocessing and the fuel fabrication stages, the PFBR will produce about 21 kg of plutonium over and above its own fuel requirement (Glaser and Ramana 2007, 94). Thus, it would take about ninety years of operation for it to produce enough plutonium for the core of a similar reactor.

48. KARP has a maximum capacity of 100 tonnes/year. Typical PHWR spent fuel has 3.75 kg of plutonium in each tonne of spent fuel. Assuming 1 per cent loss, KARP produces 371 kg of plutonium per year at 100 per cent capacity factor. The annual fuel requirement of PFBR at 75 per cent LF is 1012 kg. Even the inclusion of plutonium from PREFRE would not suffice to meet this demand.

49. The cost of removing americium has been estimated at '$18 per gram of plutonium' (NEA 1989, 64). This figure is in 1987 dollars and translates to about 1177 per gram in 2004 rupees.

50. The assumption is that the plutonium derived from reprocessing PFBR spent fuel is used almost immediately; if there are delays in such use, there would be further costs of americium removal. We neglected this possibility in our analysis.

51. The only reprocessing plant in India that deals with breeder reactor spent fuel is the one associated with the FBTR. DAE budgets show that this plant cost Rs 8.2 billion. Because the FBTR is a much smaller reactor as compared to the PFBR, it would produce no more than 200 kg of spent fuel each year (Mirchandani and Namboodiri 1981, 72). Therefore, the plant dealing with the PFBR would have to be much larger. There is a standard rule of thumb which states that costs scale with the plant capacity to the power of 0.6 (National Research Council 1996, 421). We used this rule for scaling up to obtain an estimate for the cost of reprocessing spent fuel from the PFBR. Alternate assumptions about how construction costs scale with size (see, for example, Haire 2003) lead to much higher cost projections.

52. In September 2007, the chairman of the Atomic Energy Commission announced that a reprocessing plant to deal with the PFBR spent fuel had been planned and that its construction was to commence in 2008 (Kakodkar 2007, 24). That did not happen and in January 2011, the director of IGCAR announced: ‘The design for Fast Reactor Fuel Cycle Facility is in advanced stage and Cabinet approval for it is expected soon’ (PTI 2011b). Speaking at an IAEA meeting in Vienna in early 2012, S. Raghupathy from IGCAR described FRFCF as ‘planned’ and ‘under regulatory review’ (Raghupathy 2012).

53. Worldwide experience of the reprocessing of MOX fuel from fast breeder reactors is sparse, and limited only to pilot-scale amounts (tens of tonnes in all) (NEA 1993, 234).

54. KARP took sixteen years to construct and the relatively small facility that reprocesses FBTR spent fuel took thirteen years to construct.

55. We assumed that the cost of uranium for the MOX fuel and the blankets was free. This was because there are no strong isotopic requirements for the PFBR fuel and, therefore, depleted uranium, which is available in copious quantities from reprocessing as well as uranium enrichment, could be used for this purpose (Ramana and Suchitra 2007).

56. Plutonium is about 30,000 times more radioactive than uranium-235. Therefore, fabricating it into fuel requires special facilities so that all possible contact with the material is avoided (Farmer 1983, 36).

57. Fuels for fast reactors produce much more heat per unit volume which has to be efficiently conducted away. Therefore, fuel rods have to be far thinner and structured more intricately than uranium fuel rods for PHWRs. The same difference is also true for LWRs, and it has been documented that the ‘more complex design and greater number of assemblies per tonne for the fast reactor [lead to] much higher fuel fabrication prices [than for] light water reactors’ (Farmer 1983, 37).

58. In our sensitivity analysis, we considered the possibility that fabricating costs in India are only half of what the NEA projects (Suchitra and Ramana 2011). The essential result is unchanged even in this scenario.

59. The main cost component of the PHWR is the capital cost of the reactor, which constitutes 39 per cent of the total life-cycle cost. The corresponding figure for the PFBR is 23 per cent. The main component of the total life-cycle cost at the PFBR turns out to be that of the

plutonium used in the reactor (67 per cent). In comparison, the corresponding uranium cost for the PHWR is only 27 per cent. This share of uranium cost is larger than in other countries and studies because we assumed that uranium is purchased at $200/kg, which is representative of uranium-mining costs in India. This is higher than elsewhere—for example, Canadian Energy Research Institute (CERI 2004) assumes uranium costs of about $15 to $35/kg—because of the poor quality of uranium ore in India. Assuming a lower uranium cost would only make the breeder more uneconomical.

60. In India, for example, though uranium has been mined only in the state of Jharkhand, one can find uranium even in the Himalayan ranges, albeit only at concentrations of 1.88 to 28.6 ppm (Macfarlane and Miller 2007).

61. This is true till the ore grade becomes about 1 ppm, beyond which the availability starts declining.

62. The assumption that mining ores of poorer quality will necessarily be more expensive might not be justified in the long run and the price could come down because of technological improvements. This has been the case with other minerals. For example, during the period 1900–98, world copper production increased by 2465 per cent while its constant dollar price and the average ore grade decreased by 75 per cent and seven-fold, respectively (Wilburn, Goonan, and Bleiwas 2005).

63. As discussed earlier, the NPCIL's shortage of uranium to fuel even the existing PHWRs (with a capacity of approximately 4000 MW) was caused not by a lack of uranium deposits under the ground but due to a mismatch between mining capacity and reactor requirements.

64. There is perhaps an economic reason for these projections: to hype up the demand for nuclear reactors so that vendors will lower their prices.

65. The exact overnight construction cost would depend on the distribution of this amount over time.

66. As a point of comparison, in the fiscal year 2008–09, the Nuclear Power Corporation's total income was Rs 38 billion with a profit figure after taxes of Rs 4.4 billion (NPCIL 2009, 44).

67. Worse could happen if one or more projects could not be completed because of cost overruns. In 1983, the Washington Public Power Supply System in the north-west of the United States declared bankruptcy

because it could not repay the $2.25 billion debt it had incurred to build two large nuclear plants (Pope 2008).

68. At the debates over the nuclear liability bill, for example, Prime Minister Manmohan Singh clearly represented their interests.

69. To this dictum, we may add an anecdote reflecting the DAE's view of economic costs in general. At the 1988 workshop at the Indian Institute of Science mentioned in chapter 2, during the tea break that followed a lecture on the economics of nuclear power, a senior DAE official was reportedly overheard exclaiming: 'What does atomic energy have to do with discount rates?' This was repeated to me by one of the participants.

70. If power at any expense is acceptable, then, there should be no power shortage since we could derive the required power from solar photovoltaic cells, for example.

71. As the Planning Commission's 'Integrated Energy Policy' report, 2006, opines: 'The energy policies that we have adopted since independence … have encouraged and sustained many inefficiencies in the use and production of energy. We pay one of the highest prices for energy in purchasing power parity terms … The challenge is to ensure adequate supply of energy at the least possible cost' (Planning Commission 2006). This scenario would lead one to expect that decisions on budgetary allocations would be based on sound analyses of the economics of different energy sources. This expectation is belied by the continued and ample financial support offered to atomic energy by the government.

1. Quote from Butler 2002 (48).
2. Similarly, in the 2008–09 annual report of the Nuclear Power Corporation, S.K. Jain, chairman of NPCIL and of BHAVINI—the organization responsible for the construction of the PFBR—wrote about the organization's 'culture of an overriding priority to nuclear safety' (NPCIL 2009, 19).
3. As of July 2012, the 2010–11 annual report with information up to 2010 was the latest available on the AERB website.
4. As physicist Richard Feynman (1986) wrote while discussing the problems of the United States Space Shuttle Programme, 'The fact that this danger did not lead to a catastrophe before is no guarantee that it will not the next time, unless it is completely understood. When playing Russian roulette the fact that the first shot got off safely is little comfort for the next.'
5. The first reactor, Apsara, did not undergo even a formal safety analysis (Sundararajan, Parthasarathy, and Sinha 2008, 2).
6. The NPCIL did not comply with an AERB directive to carry out integrated tests of the Emergency Core Cooling System in Kaiga I and II and RAPS III and IV before they were commissioned (Panneerselvan 1999). Of the 3200 recommendations by the AERB's Safety Review Committee for Operating Plants, the DAE and NPCIL had not complied with 375 (CAG 2012, 42).
7. For the record, Bethe felt that the development of nuclear power was 'a necessity' (Ioffe 2006).
8. The heating up of the sodium might occur as a result of, say, the cessation or slowing down of coolant flow in some part of the reactor, perhaps because of some blockage.
9. A reduction of coolant density has three effects. The reduced coolant absorbs fewer neutrons, the mean energy of neutrons is higher, and there is more leakage. In a fast reactor, higher neutron energy results in more Pu-239 fissions and, therefore, the first two effects increase reactivity. Leakage effects are important only near the periphery of the core and,

hence, become less important as a whole as the volume of the core increases.

10. A ‘dollar’ is the margin of reactivity provided by delayed neutrons, which are typically released only tens of seconds after the fission event. If the reactivity increases above unity by more than this amount, the rate of power increase is controlled by the much shorter generation time (about 10 microseconds) of prompt neutrons.

11. These tests are performed on relatively small systems and it is not completely clear whether large reactors such as the PFBR would have larger or smaller efficiencies compared to them.

12. A similar question was posed by AEC Chairman Raja Ramanna: ‘I would like to ask, are we not spending too much money on health and safety? Should we not have a look and find out whether the international standards of safety (in nuclear programmes) are indeed that necessary? … Should we follow the international standards blindly? I think we should have courage to look at these standards especially where they are leading to runaway costs’ (Ramanna 1973, cited in D. Sharma 1983 [110]).

13. To the extent possible, we have derived these descriptions from documents put out by the DAE and its sister organizations. We have used news and media reports where DAE documents were not available—or as a supplement. We have assumed that these were accurate unless there was some strong reason to not believe them. We have tried not to place too much stock on any one report. Another source of information has been the detailed annual reports entitled ‘Operating Experience with Nuclear Power Stations in Member States’ that the International Atomic Energy Agency puts out. These reports are based entirely on information that the DAE gives the IAEA—information that is highly unlikely to be given to the citizens of the country directly.

14. In 1985, an overheated cable joint at RAPS II caused a fire that spread through the cable trays and disabled four pumps (IAEA 1986, 244; Gopalakrishnan 1999a). A few years later, in 1991, there were fires in the boiler room of the same unit and the turbo generator oil system of RAPS I (IAEA 1992, 394–96). In 1989, a large spark was observed from slip rings on the exciter end of the turbine in MAPS I; there were also two

other fires in the same reactor near the primary heat transport system (IAEA 1990, 298).

15. Unfortunately, this sort of analysis may no longer be possible. Starting in 2005, IAEA does not give information on each outage but aggregates them into various ‘outage causes’. Thus, the kind of detail that is needed to perform historical analyses of different kinds of accidents is no longer available in the public domain.

16. For example, Bajaj and Gore (2006) state that ‘The event was analyzed in depth and corrective measures were taken not only at Kakrapar Atomic Power Station but at other stations and projects also’ and list some ‘salient recommendations’: ‘(i) All the entry points of pipe tunnels/cable trenches to the basement of all buildings having safety-related equipment are sealed with multiple barriers. (ii) The openings (like manholes, ventilation points) are either raised above design basis flood level, or are sealed. (iii) A number of administrative measures (like maintenance/inspection of flood prevention measures) and review/modifications of flood protection plans/emergency operating procedures’.

17. Such practices led some years later to a fire involving many cans of paint on the same dome (ToI 1999a).

18. This is clearly a worst-case scenario and might seem far-fetched. But, as sociologist Lee Clarke argues, there is value in engaging in constructing such scenarios because disasters, even worst-case ones, are a part of life (Clarke 2006). Analysing them can lead to insights.

19. There have been previous instances of strikes at BARC, including one by operators in the CIRUS and Dhruva reactors in June 1992 (AERB 1993, 10).

20. These badges measure cumulative exposure over a period of time, and are meant to be periodically submitted to the Health Physics department for assessment. The practice of inadequate methods of detecting high levels of radiation seems to continue. In 2011, workers at the Kakrapar reactor found that the radiation detectors they were given did not record beyond a certain value, whereas they had been asked to work in a zone that had nearly twenty times that level of radiation (Banerji 2011).

21. On the resultant risks to health, see chapter 8.

22. Listed below are just those from the period between 1995 and 2000. Operating records reveal repeated oil leaks occurred in Kakrapar II in 1995 (IAEA 1996, 306). In 1997, there were oil leaks in Kalpakkam II and a hydrogen leak in Kakrapar II (IAEA 1998, 304–08). In 1999, there was another hydrogen leak in Kakrapar II, as well as one in Narora II (IAEA 2000, 288–96). In 2000, there were hydrogen leaks in Narora I, Narora II and RAPS III, and oil leaks in RAPS III and Kaiga II (IAEA 2001, 294–312).

23. Another recurring problem at this reactor is leaks from a primary feed-water pump recirculation line.

24. The DAE used to offer an official document on its website titled 'Nuclear Emergencies—How to Respond' (DAE N.D.). The DAE first argues at length that it is 'extremely unlikely that the public near a nuclear facility will be exposed to any radiation beyond the permissible limits'. But it suggests that 'if you still feel concerned on hearing any news or rumour about an incident at a nearby nuclear facility, follow these simple guidelines'. Among its list of Dos are: 'Go indoors. Stay inside', 'Close doors and windows', 'Cover all food, water and consume only such covered items', and 'Extend full cooperation to local authorities and obey their instructions completely—be it for taking medication, evacuation, etc.' Its list of Don'ts includes: 'Do not panic', 'Do not believe in rumours passed on by word of mouth from one person to another', and 'Do not disobey any instruction of the District or Civil Defence Authorities who would be doing their best to ensure the safety of yourself, your family and your property'. The DAE appears to have removed this document.

25. The populations of Mandvi and Mangrol, according to the 2001 Census, are about 45,000 and 55,000 respectively.

26. Since the early 1980s, the Nuclear Energy Agency of the OECD and the IAEA have been operating a reporting system wherein about thirty countries report safety-related events every year. Over twenty-five years of operation it has gathered more than 3250 reports (NEA 2006, 9).

27. Analogously, as US Secretary of Defense Donald Rumsfeld put it, 'there are known knowns; there are things we know we know. We also know there are known unknowns; that is to say, we know there are some

things we do not know. But there are also unknown unknowns—the ones we don't know we don't know'.

28. This was stated somewhat differently by a committee appointed by the US Nuclear Regulatory Commission which pointed out that it is 'conceptually impossible to be complete in a mathematical sense in the construction of event-trees and fault-trees', the methodology used to calculate probabilities, and this 'inherent limitation means that any calculation using this methodology is always subject to revision and to doubt as to its completeness' (Lewis et al. 1978, ix). This begs the question: Why does the nuclear establishment come up with statements like 'the core damage frequency [for TAPS] is around 7.0E-05/Reactor year', that is, the probability of an accident that damages the core of the reactor is 70 parts per million during each year that the reactor operates (Koley et al. 2006)? Such assessments of probability of accidents are problematic and should not be taken seriously (Ramana 2011a). In addition to the problem of unaccounted-for accident pathways, if one looks at the details underlying such a calculation, one always comes up with unproven assumptions of various kinds. One reason for experts resorting to such detailed technical calculations that are, in practice, unverifiable and incredible, is that they serve to mystify discussions which should ideally involve people who are put at risk from these facilities, and who should be involved in decisions about locating, constructing and operating them.

29. This is elaborated by Kumar and Ramana (Forthcoming).

30. First, there was no redundancy that would prevent mixing of high-level and low-level waste, or protect workers, in case of valve failure. Valves are known to fail despite measures to improve their reliability. Second, the plant had been operating for five years without any monitors in the region to detect radiation levels. There was no procedure that would alert workers to high radiation levels before they received large doses.

8. ENVIRONMENT AND HEALTH

1. The term medium-level waste (MLW) has also been used, presumably as a synonym for intermediate-level waste.
2. While the Trombay and Tarapur reprocessing plants have associated vitrification plants, the DAE appears to have real difficulties in setting up the same at Kalpakkam. Since KARP was commissioned in 1998, the only statements about vitrification there have been in the future. For example, in 2008, the BARC director reportedly said that the plant ‘will soon become operational’ (R. Prasad 2008). Two years later, at the Asian Nuclear Prospects conference, S.D. Misra of BARC’s Nuclear Recycle group said that the Kalpakkam vitrification plant was ‘under construction’ (Misra 2011, 480). The 2010–11 DAE annual report mentions only ‘trials’ of one of the components of the vitrification plant (DAE 2011, 8). This implies that a considerable amount of HLW must be stored in liquid form in tanks, which poses a safety hazard.
3. The two are not mutually exclusive. Uranium, for example, is harmful to the body if ingested, both because it is radioactive and because it can accumulate in the kidneys and cause renal failure.
4. In the bone, however, the energy deposition due to a roentgen of radiation is significantly larger; hence, the number of rads is much larger than the number of roentgens (Glasstone and Sesonske 1981, 566–67).
5. A linear model requires that there be no minimum threshold dosage for health risks. It is believed that, for cancers and other genetic effects, there is no threshold (BEIR 1988, 177). Public health criteria in many countries are based on a no-threshold, linear model.
6. An analogy might clarify. Imagine that a medical company produces ten thousand tablets of which ten are contaminated with a fatal poison. These ten tablets are randomly distributed amongst the produced inventory. If all the ten contaminated tablets are sent to one town, there will be ten fatalities in that town. However, if they end up in various places all over the country, there will still be ten deaths. In the latter instance, because these fatalities will be spread out across the country, it would be much more difficult to pinpoint the cause.

7. This is at the Jaduguda mines, the richest uranium deposit (Sarkar 1984, 193).

8. HLW contains a much higher concentration of radioactivity than spent fuel. See chapter 4 for more details.

9. This was the year that the first commercial nuclear reactor in the United States came online. It was also the year that saw three nuclear accidents in three countries: the fire at the Rocky Flats plant that manufactures plutonium pits for US nuclear weapons, an explosion at a nuclear waste storage site in Kyshtym in Russia, and a fire in a nuclear reactor at Windscale, United Kingdom.

10. The site was chosen in 1987 and in 2009, the Obama administration abandoned this idea.

11. The Thermal Oxide Reprocessing Plant, a major source of waste at Sellafield, has since been shut down (Brown 2003).

12. This is the dose integrated up to 10,000 years.

13. This documentary film can be seen on the Internet on YouTube.

14. Some of these could have presumably been prevented if only the villagers had access to the kind of health care provided by UCIL to the proximate villagers.

15. In fact, the SKV survey explicitly included questions about food and concluded that those near Jaduguda were better fed.

16. For example, when the Rawatbhata epidemiological survey results came out, one of the responses was ‘radiation from the Rajasthan power station … has been continuously monitored and no dangerous level of radiation has been released outside’ (Kanavi 1994).

17. Unfortunately, comprehensive studies of these impacts as well as synergistic effects of the combined exposure to both radioactive and toxic pollutants are yet to be carried out.

18. Some parts of the Kerala coast have high levels of thorium in the sand. That is the source of the high radiation levels.

19. The majority of the population in the villages near Jaduguda, of course, consists of people who do not come into direct contact with uranium, except for what is in the ambient environment.

20. Even though the average concentration of radon in the Jaduguda mines is low because of the poor quality of uranium ore, there will always be

‘pockets of higher … radon concentrations’ (Raghavayya and Khan 1989, 93).

21. Another medical condition that could lead to lung problems and has been found to afflict uranium workers is an autoimmune disorder called lupus (Conrad et al. 1996).

22. Organically bound tritium also delivers energy more effectively than tritiated water and therefore imparts a higher radiation dose (Chen 2006).

23. A special concern with tritiated water is that when ingested by pregnant women, it can pass through the placenta, and affect the foetus. During this stage, the developing organism (the embryo and the foetus) is highly radiosensitive (ICRP 2003).

24. The details are discussed in chapter 7. See also Ramana and Kumar 2010.

25. The latter amount is dangerously high—a worker would receive more than the annual limit if he or she were to work in this atmosphere for just an hour.

26. According to the ICRP, a dose of 20 mSv leads, on an average, to an approximately 1 in a 1000 chance of dying from radiation-induced cancer. A dose that is twice as large would lead to twice the probability of getting cancer.

27. In another incident on 20 November 2001, there was a smaller leak involving 1.4 tonnes of heavy water at the Narora I reactor; one person involved in the mopping-up operations received a radiation dose of 18.49 mSv (AERB 2002, 18).

28. The DAE’s reaction to the publication of the article containing these details was to try to ‘amend the 1962 act to increase punishment for unauthorized disclosure to 5 years rigorous imprisonment instead of 3 earlier and to allow them to prosecute without first seeking the solicitor general’s approval’ (Gadekar 2005).

29. Herein lies one problem with the notion of risk as is commonly used—that the hazard possibility that underlies the risk calculation is not always stochastic, the way the association of probability figures would suggest. Rather, the risk involved in an activity depends on the control exercised by the worker in the workplace. British radiation safety professional Dave Rosenfeld offers this example: ‘Ask a worker at the Windscale nuclear fuel reprocessing plant to repair pipework in a high-radiation area

unfamiliar to him. Even if there are only a couple of lethal "hotspots" where doses are high, the whole area appears hazardous. To him (women are not employed in high-radiation zones) a walk in a straight line is like crossing the road blindfold. As the management gives him a chart of hotspots and a pocket alarm meter, he feels sure to avoid deadly spots, confidently and consistently—as long as experience tells him that the management or union safety committee have assured the chart and meter are reliable' (Rosenfeld 1984, 43).

30. One example is Gopi Rethinaraj, who held a master's degree in physics and so could understand relatively technical material. Reading one such report on heavy water, Rethinaraj found a passing reference to the extraction of tritium from irradiated heavy water in Indian reactors. He rightly recognized the importance of such tritium for thermonuclear weapons and wrote about this in an international defence journal (Rethinaraj 1998). Soon after, Rethinaraj found that he was not being allowed into the DAE's press conferences (Subbarao 1998). Being denied entry into such DAE events would, in effect, result in the journalist's not being able to cover the nuclear beat. Rethinaraj ended up quitting journalism and pursuing an academic career.

31. Witness, for example, the exchange between Rangarajan Kumaramangalam, then minister of state for science and technology, and Member of Parliament Surender Reddy, after the minister had laid a statement about the Narora fire (see chapter 7) on the table in the Lok Sabha on 28 July 1993 (Kumaramangalam 1993). The statement talked about the two separate committees, one under the Nuclear Power Corporation and one under the Atomic Energy Regulatory Board, that had been set up to study the causes of this fire and Reddy pointed out that there were reports that the two committees were not unanimous in their reports. While beginning his intervention, Reddy had started by saying 'Mr Speaker, Sir, we must thank the providence that the fire did not affect the Reactor building. Two Committees were set up after that which have gone into …' At which point, the Speaker immediately cut him off saying, 'May I again caution the Member that if you put questions which create scare in the minds of people, it is not going to be useful. The fire in the reactor and the fire in other part of the building are two different things. Please be careful about it.' Only after Reddy had assured the

House that he was ‘very very careful. I know what I am talking’, was he allowed to continue. When Reddy referred to the differences between the committees, Minister Kumaramangalam responded: ‘In fact, there has been no divergence at all in two Committee reports’. This was, in fact, not true, and the AERB report went much further than the NPCIL report and identified ‘several serious lacunae, which then existed in DAE’s overall approach to safety management’ (Gopalakrishnan 2002, 385).

32. Interestingly, the corresponding survey carried out in Pakistan a couple of years later found that 92 per cent of those polled had a similar view about the environmental costs (Ahmed and Cortright 1998, 116).

CONCLUSION

1. Perhaps the most striking example of revision of breeder plans is that of France. The French Atomic Energy Commission had announced a three-stage plan for nuclear power involving breeder reactors and thorium a month before Bhabha talked about the same in India. It constructed three breeder reactors, including the commercial scale Superphénix. That reactor was abandoned in 1998 and there is no follow-on breeder reactor planned for at least a decade (IPFM 2010a, 11). Of course, there are still some anachronistic breeder enthusiasts in France, but their claim on the energy policymaking process is weak to non-existent.
2. According to the 2012 'World Nuclear Industry Status Report', nuclear generation reduced by 112 TWh or 4.3 per cent relative to 2010; a total of twenty-one reactors were shut down, ten in Japan, eight in Germany and one in the United Kingdom (Schneider, Froggatt, and Hazemann 2012, 10–12).
3. The nuclear establishment and the government are loath to admit to having been forced to change their plans by popular resistance.
4. This also means that there is no reason to construct breeder reactors or thorium-based reactors with all their problems.
5. Similar tendencies have been noted in nuclear cost estimates in other countries too (Mackerron 1992).
6. The fallout from the Chernobyl accident was detected in Bombay and Jodhpur, and air concentrations of radionuclides like iodine-131 and caesium-137 went up by factors of twenty or more in some cases (Gopalakrishnan and Mishra 1987, 15).
7. There were exceptions. In the mid-1990s, the member in charge of energy in the Planning Commission was an officer from the Indian Administrative Service (IAS) who had headed the Securities and Exchange Board of India. Because of how uneconomical nuclear power had been, he recommended that India discontinue nuclear power projects (M.R. Srinivasan 2002, 198). But he was succeeded by a former AEC chairman, who immediately reversed course and persuaded the deputy chairman of the commission to suggest further investments in nuclear power to the government.

8. One government body that has been somewhat critical of the DAE is the Comptroller and Auditor General, whose reports have been discussed in chapters 1, 5 and 7. But the CAG has little or no role in energy policymaking.

9. The THORP plant has been shut down for many years, and may remain closed for several more years, because of a series of technical problems (Brown 2003; Vidal 2009).

10. See brochure on advanced heavy water reactor with LeU-Th MOX fuel at http://www.dae.gov.in/gc/ahwr-leu-broc.pdf

11. We have already discussed the case of the PFBR in chapter 2, Box 2.3: Dual Use or Misuse. In addition, each of the 220-MW PHWRs that were not put on the civilian list could produce up to 150 or 200 kg of weapon-grade plutonium, the kind preferred by nuclear weapon designers, each year (Mian et al. 2006).

12. Slow neutrons are also called thermal neutrons.

13. This water is purified so as to ensure that the concentration of neutron-absorbing impurities is very small. The term light water is used to distinguish these reactors from reactors using heavy water.

14. This description draws from Bajaj and Gore 2006; Bergeron 2002; Patterson 1976.

15. Steam cannot efficiently carry away the heat from the fuel elements.

16. The reason for refuelling simultaneously in adjoining channels is so that the fuel near both reactor ends has an equal mixture of fresh and nearly fully irradiated fuel, and ‘thus of approximately the same average reactivity as the half-spent fuel at the centre’ (Millar 1976, 359).

17. It has been argued that this has negative implications for safety because ‘the area of the primary pressure envelope has been enhanced several times’ resulting in ‘a primary heat transport system’ with a much greater surface area. This is further increased by the use of online refuelling, when ‘the refuelling machine becomes a part of the primary pressure envelope’. The surface of these high-pressure tubes is exposed to high neutron fluxes, unmediated by any shield, resulting in an increased ‘risk of mechanical failure due to neutron creep and other weakening effects’ (Kamath 1990).

18. If thorium is used, then there could also be breeder reactors with only slow neutrons; these are called thermal breeder reactors.

1. The nuclear section of the statement is not immediately apparent, coming as it does after agreements on the economy, energy and environment, democracy and development, and non-proliferation and security, and after three other commitments on high technology and space.
2. The reactors that were already under safeguards were TAPS I and II, and RAPS I and II. At that time, Koodankulam I and II were to join these ranks if and when completed.
3. Of these, RAPS V and VI were put under safeguards in October 2009, RAPS III and IV in March 2010, and Kakrapar I and II in December 2010 (IAEA 2010).
4. Together, these unsafeguarded reactors have a combined electricity generation capacity of 2350 MW.
5. This has been elaborated on in Box 2.3 in chapter 2. See also Glaser and Ramana 2007 and Mian et al. 2006.
6. The Prime Minister’s Office did try to dismiss Kakodkar’s interview as inconsequential, stating, ‘This view is just one viewpoint. There are many other viewpoints which will have to be taken into account by any government while arriving at an overall policy decision … the Atomic Energy Commission is just one of the departments.’ (Abraham 2007, 30).
7. A second reason why Kakodkar could not be fired was that ‘such an action would be construed as direct evidence that U.S. pressure on the Indian government was real’ (Abraham 2007, 30).
8. For example, in his statement after the House of Representatives passed the Hyde Act, President Bush stated, ‘The U.S.–India civil nuclear cooperation initiative will help India generate more nuclear power to meet its enormous energy needs in a manner that does not increase greenhouse gas emissions and air pollution, or increase demand on global oil and gas supplies’ (reproduced in Bhonsle, Prakash, and Gupta 2007 [244]).
9. Grover was the main representative of the DAE at the negotiations of the US–India deal.
10. Rice’s focus was not only military. In the same article, she points out: ‘International economic policies that leverage the advantages of the

American economy and expand free trade are the decisive tools in shaping international politics. They permit us to reach out to states as varied as South Africa and India.'

11. During President Bush's first term in office, the two countries signed the 'Next Steps in Strategic Partnership' agreement, which announced that the United States would help India with its civilian space programmes, high-technology trade, missile defence aid, and its civilian nuclear activities. The purpose of this 'Strategic Partnership' accord was made clear by a US official who said the 'goal is to help India become a major world power in the 21st century … We understand fully the implications, including military implications, of that statement' (AFP 2005).
12. As Ashley Tellis wrote (2005a, 41): 'If the United States is serious about advancing its geopolitical objectives in Asia, it would almost by definition help New Delhi develop strategic capabilities such that India's nuclear weaponry and associated delivery systems could deter against the growing and utterly more capable nuclear forces Beijing is likely to possess by 2025.'
13. Commenting on the NSG waiver and the US Congress agreement to nuclear exports to India in October 2008, Seth Grae, president of the company, said that the agreement 'enables us to pursue new opportunities in what is estimated to be a $150-billion nuclear marketplace. We have been engaged in serious discussions with many entities in the private sector and government … Our immediate goal is to accelerate those discussions so that we can consolidate many of the new business opportunities before us. India is an exciting market and we are proud to participate in the development of what promises to be one of the fastest-growing nuclear markets' (Menezes 2008).
14. The USIBC 'is housed, conveniently, in the U.S. Chamber of Commerce in Washington'; the latter is deeply interested in breaking down 'walls erected in India to protect the national economy' (Prashad 2007).
15. In 2008, Blackwill joined Rand Corporation and is part of the Project on National Security Reform.
16. Official government estimates of the cost of the Chernobyl accident run into hundreds of billions of dollars.

APPENDIX 3: THE ENVIRONMENTAL IMPACT ASSESSMENT PROCESS

1. The Expert Appraisal Committee is a group of people with expertise in a variety of fields appointed by the government to evaluate the project application and other material and offer a recommendation about clearing the project.
2. Even in the case of the one project where the location had to be shifted because of fears of contamination of drinking water, the processing plant to deal with uranium ore from the Lambapur-Peddagattu deposit in Andhra Pradesh, the pathway and the potential impact of such contamination were not identified in the EIA, which merely offered the assurance that 'effluents generated at the plant shall be treated to standards specified' before discharge (MECON 2003, 5-1).
3. For an explanation, see chapter 7.
4. For example, the EAC that dealt with the clearance for the Kakrapar Atomic Power Plant Units III and IV included the Secretary of AERB, a former Secretary of AERB, a former head of the Risk Studies Division, Indira Gandhi Centre for Atomic Research, a former managing director of Indian Rare Earths, and a retired senior executive director of NPCIL (Mauskar 2007). Thus, five of the twelve members were or had been associated with the DAE.
5. In the case of the Koodankulam reactors, where my colleague Divya obtained the written responses through the Right to Information Act, the Nuclear Power Corporation, that was to operate these reactors, offered mostly cut-and-paste responses. By our reckoning, there were at least forty-five different questions, whereas NPCIL only had thirty-one responses (Ramana and Rao 2010).
6. As mentioned in chapter 2, in 2005, the DAE had suggested to the MoEF that some of its projects be exempted from any public consultation requirement (Menon and Ramana 2007, 18).